

IN THE UNITED STATES DISTRICT COURT
FOR THE DISTRICT OF DELAWARE

RIVERBED TECHNOLOGY, INC.,)	
)	
Plaintiff,)	
)	
vs.)	Civil Action No. _____
)	
QUANTUM CORPORATION, a Delaware)	
Corporation, A.C.N. 120 786 012 PTY. LTD.,)	
an Australian Company, and ROCKSOFT)	TRIAL BY JURY DEMANDED
LTD., an Australian Company,)	
)	
Defendants.)	

COMPLAINT

Plaintiff Riverbed Technology, Inc. ("Riverbed") by and through its undersigned counsel, hereby complains against Quantum Corporation ("Quantum"), A.C.N. 120 786 012 Pty. Ltd. ("A.C.N. 120"), and Rocksoft Limited ("Rocksoft") (collectively "Defendants") as follows:

PARTIES

1. Riverbed is a corporation organized and existing under the laws of the State of Delaware, having a principal place of business at 199 Fremont Street, San Francisco, California, 94105. Riverbed is the technology and market leader in wide area data services (WDS). Riverbed designs, builds, and sells devices that facilitate the efficient sharing of computer data over extended, or wide-area, computer networks. Riverbed's technology is used to, among other things, improve the performance of everyday computer applications, such as e-mail, file sharing, and document management, by a broad range of companies. Riverbed has developed and patented pioneering technologies applicable to wide area data services applications as well as other applications, such as data storage applications.

2. Quantum is a corporation organized and existing under the laws of the State of Delaware, having a principal place of business at 1650 Technology Drive, Suite 700, San Jose, CA 95110.

3. Upon information and belief, A.C.N. 120 is an Australian company organized and existing under the laws of Australia, with a place of business at 175 Fullarton Road, Level 1, Dulwich, SA 5065, Australia.

4. Upon information and belief, Rocksoft is an Australian company organized and existing under the laws of Australia, with a place of business at 175 Fullarton Road, Level 1, Dulwich, SA 5065, Australia.

5. Upon information and belief, Quantum is the parent company to defendants A.C.N. 120 and Rocksoft. Upon information and belief, Rocksoft is a subsidiary of A.C.N. 120.

JURISDICTION AND VENUE

6. This Court has subject matter jurisdiction over this complaint pursuant to 28 U.S.C. §§ 1331 and 1338 because this action includes claims of infringement under the patent laws of the United States, 35 U.S.C. § 1 et seq., and pursuant to 28 U.S.C. §§ 2201 and 2202 because this action includes declaratory judgment claims. Specifically, this action includes declaratory judgment claims of non-infringement and invalidity of U.S. Patent No. 5,990,810 ("the '810 patent") (Exhibit A).

7. Personal jurisdiction over Defendants comports with the United States Constitution, Delaware's long-arm statute and the Federal Rules of Civil Procedure. Quantum, A.C.N. 120, and Rocksoft are subject to the jurisdiction of this Court for at least the following reasons. Quantum is subject to the jurisdiction of this Court because Quantum does business in and is incorporated under the laws of Delaware. A.C.N. 120 and Rocksoft are subject to the jurisdiction of this Court because (1) both are current or past assignees of the '810 patent that

have directly or indirectly alleged through Quantum, a Delaware corporation, that Riverbed infringes the '810 patent in the United States, which includes the District of Delaware, and (2) A.C.N. 120 and Rocksoft have authorized Quantum to assert patent infringement claims under the '810 patent against Riverbed in the United States, which includes the District of Delaware. A.C.N. 120 is also subject to the jurisdiction of this Court because (1) upon information and belief, it is a patent holding subsidiary of its parent Quantum, which is a Delaware corporation, that has alleged infringement Riverbed, also a Delaware corporation, and (2) it is subject to Federal Rule of Civil Procedure 4(k)(2). Rocksoft is also subject to the jurisdiction of this Court because, upon information and belief, Rocksoft does business in Delaware and has sold and/or offered to sell Rocksoft products that incorporate the purported inventions of the '810 patent through its website which is accessible throughout United States, including the District of Delaware.

8. Venue in this District is proper under 28 U.S.C. §§ 1391(b) and (c), and 1400(b), because Defendants are subject to personal jurisdiction in the District of Delaware.

EXISTENCE OF AN ACTUAL CONTROVERSY

9. There is an actual controversy within the jurisdiction of this Court under 28 U.S.C. §§ 2201 and 2202.

10. Quantum filed a patent infringement complaint against Riverbed in the Northern District of California in August 2007 alleging that Riverbed has manufactured, sold, offered to sell and/or imported Riverbed Steelhead products that infringe the '810 patent. Quantum also alleged in its complaint that the '810 patent is valid and meets all the requirements of 35 U.S.C. § 1 et seq.

11. During the Northern District of California action, Riverbed became aware that, as of the filing of its complaint, Quantum had not obtained any rights in the '810 patent, either by exclusive license or assignment, and thus lacked standing to assert the '810 patent against

Riverbed. Upon information and belief, Riverbed now believes that Rocksoft and/or A.C.N. 120 are assignees of the '810 patent and Quantum is an exclusive licensee of the '810 patent due to actions taken after the filing of its complaint. Riverbed intends to immediately file a motion to dismiss Quantum's patent infringement claims under the '810 patent in the Northern District of California because Quantum did not have standing at the time that lawsuit was filed and therefore that court does not have subject matter jurisdiction over Quantum's claims and Quantum cannot cure its standing defect.

12. Based on Quantum's conduct in filing of a patent infringement lawsuit in August 2007 and subsequent discovery that it did not have standing to sue, Quantum and its subsidiaries A.C.N. 120 and Rocksoft have created in Riverbed a reasonable apprehension that Quantum, A.C.N. 120 and Rocksoft will initiate yet another patent infringement suit against Riverbed, alleging that Riverbed infringes the '810 patent.

13. Consequently, an actual and justiciable controversy exists between Riverbed and Quantum, A.C.N. 120 and Rocksoft as to whether the patents-in-suit are invalid and/or infringed. Absent a declaration of invalidity and/or noninfringement, Quantum, A.C.N. 120 and Rocksoft will continue to wrongfully assert the '810 patent against Riverbed.

FIRST CAUSE OF ACTION
(Declaratory Judgment of Non-Infringement)

14. Riverbed incorporates the allegations in paragraphs 1 through 13 of this complaint as if fully set forth herein.

15. Riverbed's products do not infringe, either directly or indirectly, any claim of the '810 patent.

16. An actual controversy, within the meaning of 28 U.S.C. §§ 2201 and 2202, exists between Riverbed and Quantum, A.C.N. 120 and Rocksoft. Riverbed seeks a judgment that it does not infringe the '810 patent.

SECOND CAUSE OF ACTION
(Declaratory Judgment of Invalidity)

17. Riverbed incorporates the allegations in paragraphs 1 through 16 of the complaint as if fully set forth herein.

18. The '810 patent is invalid for failure to satisfy one or more of the conditions of patentability set forth in Part II of Title 35 of the United States Code, including, but not limited to, 35 U.S.C. §§ 101, 102, 103 and 112.

19. An actual controversy, within the meaning of 28 U.S.C. §§ 2201 and 2202, exists between Riverbed and Quantum, A.C.N. 120 and Rocksoft. Riverbed seeks a judgment that the '810 patent is invalid.

EXCEPTIONAL CASE

20. This is an exceptional case entitling Riverbed to an award of its attorneys' fees incurred in connection with defending and prosecuting this action pursuant to 35 U.S.C. § 285, as a result of, *inter alia*, Quantum's attempted assertion of the '810 patent against Riverbed with the knowledge that the '810 patent is not-infringed and/or invalid.

REQUEST FOR RELIEF

WHEREFORE, Riverbed respectfully requests the following relief:

a. A judgment declaring that Riverbed has not infringed and is not infringing any claim of the '810 patent, and that Riverbed has not contributed to or induced and is not contributing to or inducing infringement of any claim of the '810 patent;


- b. A judgment declaring that each claim of the '810 patent is invalid;
- c. A judgment declaring this to be an exceptional case under 35 U.S.C. § 285 and awarding Riverbed its costs, expenses, and reasonable attorneys' fees;
- d. That the Court award Riverbed such other and further relief as the Court deems just and proper.

DEMAND FOR JURY TRIAL

Pursuant to Fed. R. Civ. P. 38(b), Riverbed demands a trial by jury on all issues so triable.

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Riverbed Technology, Inc.

Dated: January 9, 2008

EXHIBIT A



US005990810A

United States Patent

[19]

Williams[11] **Patent Number:** **5,990,810**[45] **Date of Patent:** **Nov. 23, 1999**

[54] **METHOD FOR PARTITIONING A BLOCK OF DATA INTO SUBBLOCKS AND FOR STORING AND COMMUNICATING SUCH SUBBLOCKS**

[76] **Inventor:** Ross Neil Williams, 3/305 N Terrace, Adelaide SA5000, Australia

[21] **Appl No:** 08/894,091

[22] **PCT Filed:** Feb. 15, 1996

[86] **PCT No:** PCT/AU96/00081

§ 371 Date: Aug. 15, 1997

§ 102(c) Date: Aug. 15, 1997

[87] **PCT Pub No:** WO96/25801

PCT Pub Date: Aug. 22, 1996

[30] **Foreign Application Priority Data**

Feb 17, 1995	[AU]	Australia	PN1232
Apr 12, 1995	[AU]	Australia	PN2392

[51] **Int. Cl.⁶** H03M 7/00

[52] **U.S. Cl.** 341/51; 341/67

[58] **Field of Search** 341/51, 50, 67; 375/241; 704/203

[56] **References Cited**

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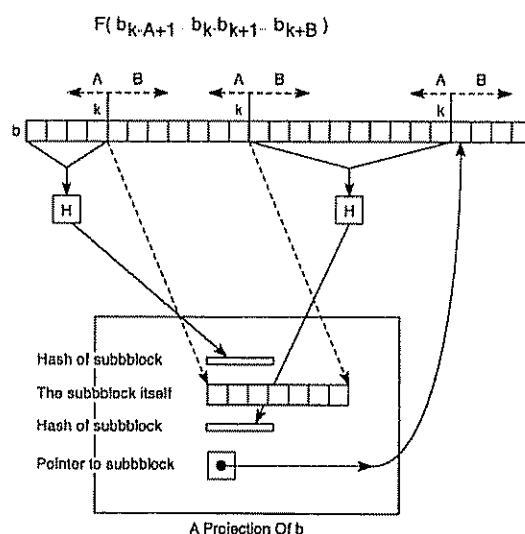
Primary Examiner—Brian Young

Attorney, Agent, or Firm—Greenberg Traurig; Robert P. Bell

[57] **ABSTRACT**

This invention provides a method and apparatus for detecting common spans within one or more data blocks by partitioning the blocks (FIG 4) into subblocks and searching the group of subblocks (FIG 12) (or their corresponding hashes (FIG 13)) for duplicates. Blocks can be partitioned into subblocks using a variety of methods, including methods that place subblock boundaries at fixed positions (FIG 3), methods that place subblock boundaries at data-dependent positions (FIG. 3), and methods that yield multiple overlapping subblocks (FIG. 6). By comparing the hashes of subblocks, common spans of one or more blocks can be identified without ever having to compare the blocks or subblocks themselves (FIG. 13). This leads to several applications including an incremental backup system that backs up changes rather than changed files (FIG. 25), a utility that determines the similarities and differences between two files (FIG. 13), a file system that stores each unique subblock at most once (FIG 26), and a communications system that eliminates the need to transmit subblocks already possessed by the receiver (FIG 19).

30 Claims, 26 Drawing Sheets



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MADD 0003
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Demonstr	ates con	tent mis	alignmen	t.
XDemonst	rates co	ntent mi	salignme	nt.

Figure 1

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| Fixed an | d variab | le width | partiti | oning. |
| Fixe | d an | d variable wid | th part | itioning. |

Figure 2

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Data-indep	endent	partitioning.
XData-inde	pendent pa	rtitioning .

Data-dep	endent	partiti	oning.
XData-dep	endent	partiti	oning.

Figure 3

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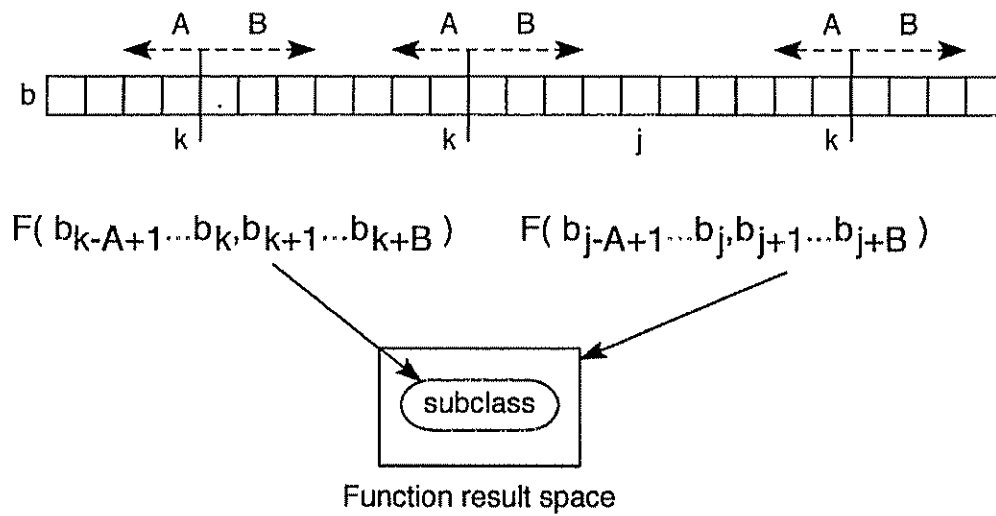


Figure 4

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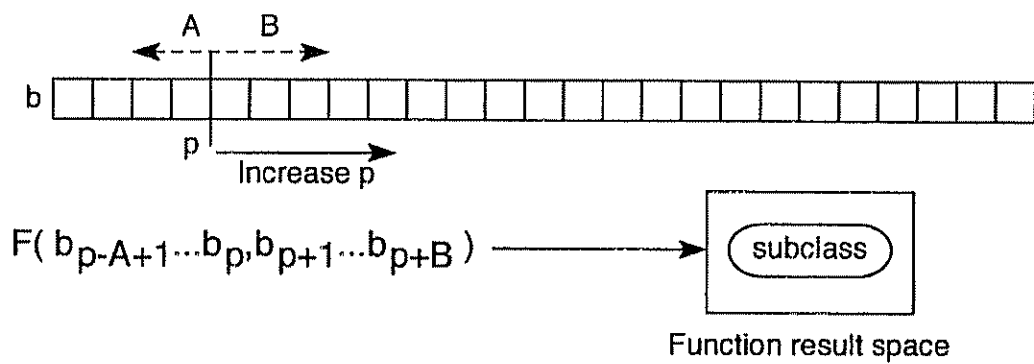


Figure 5

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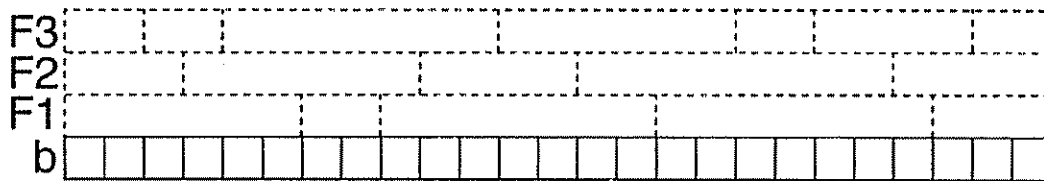


Figure 6

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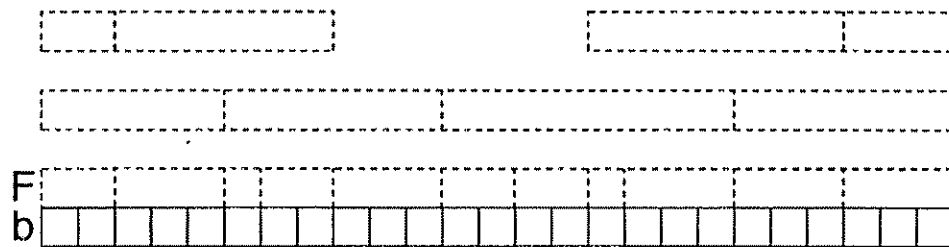


Figure 7

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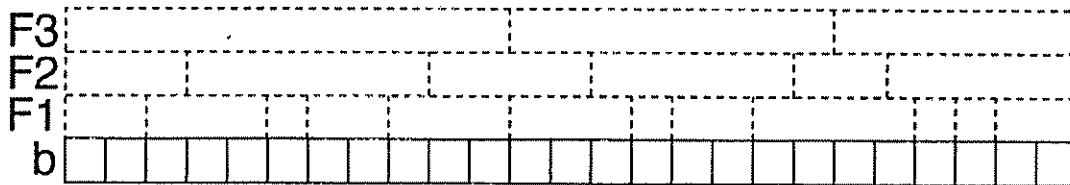


Figure 8

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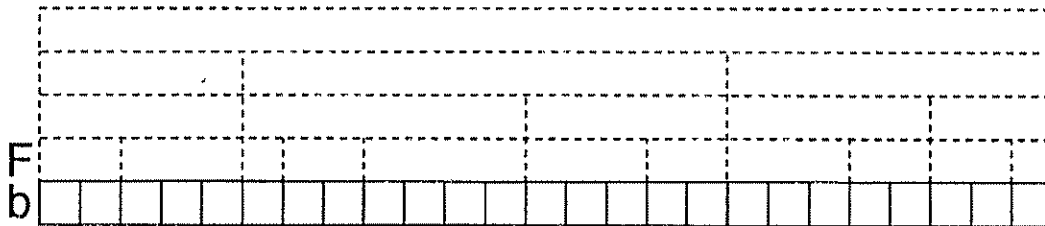


Figure 9

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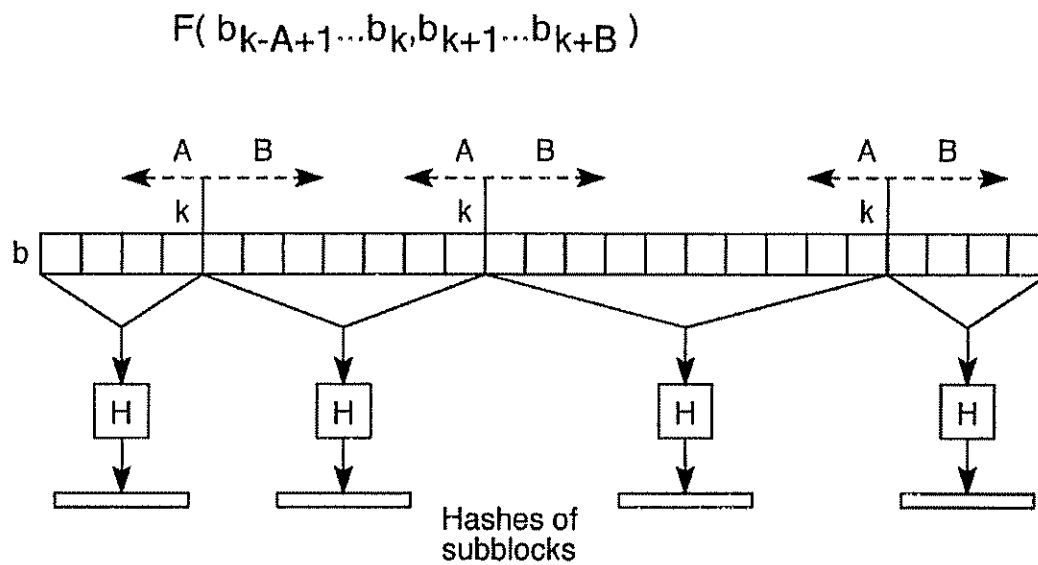


Figure 10

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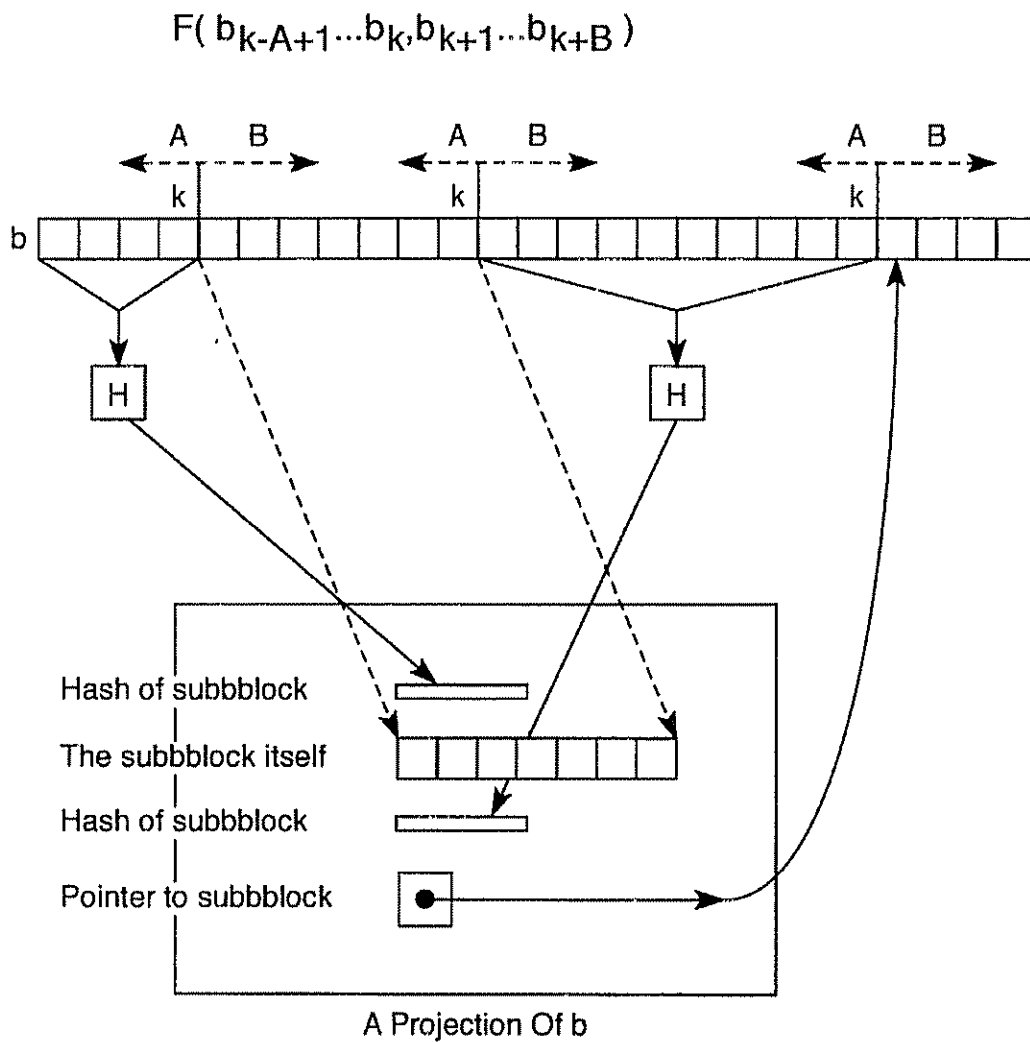


Figure 11

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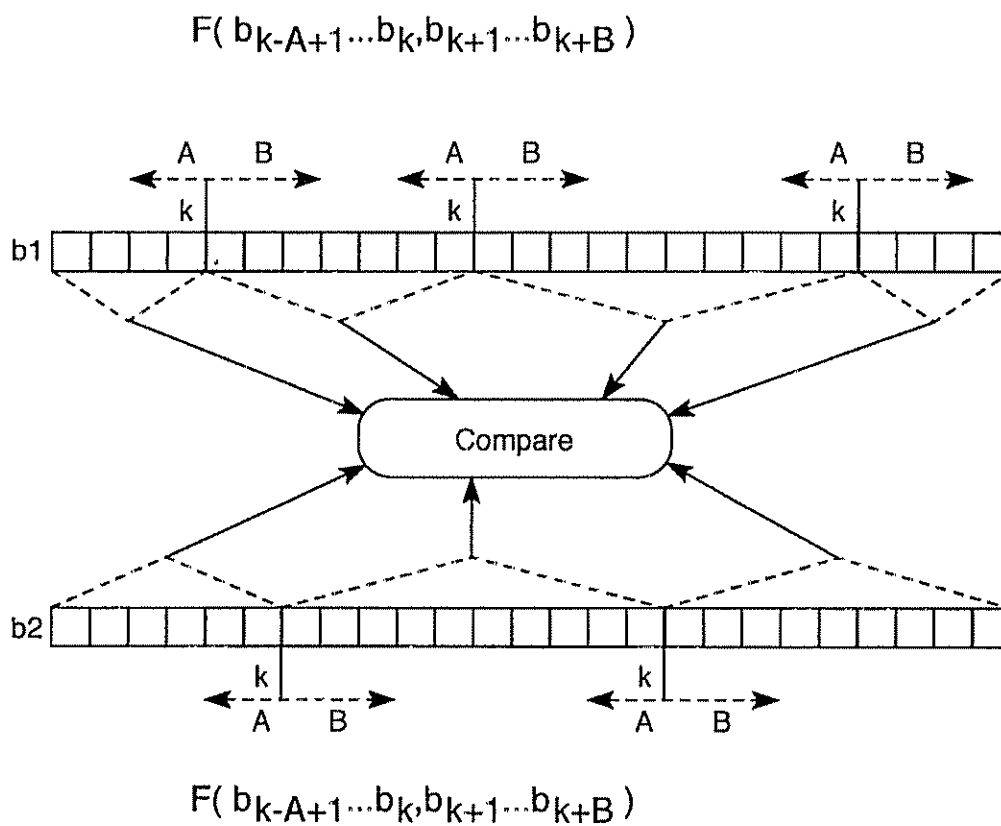


Figure 12

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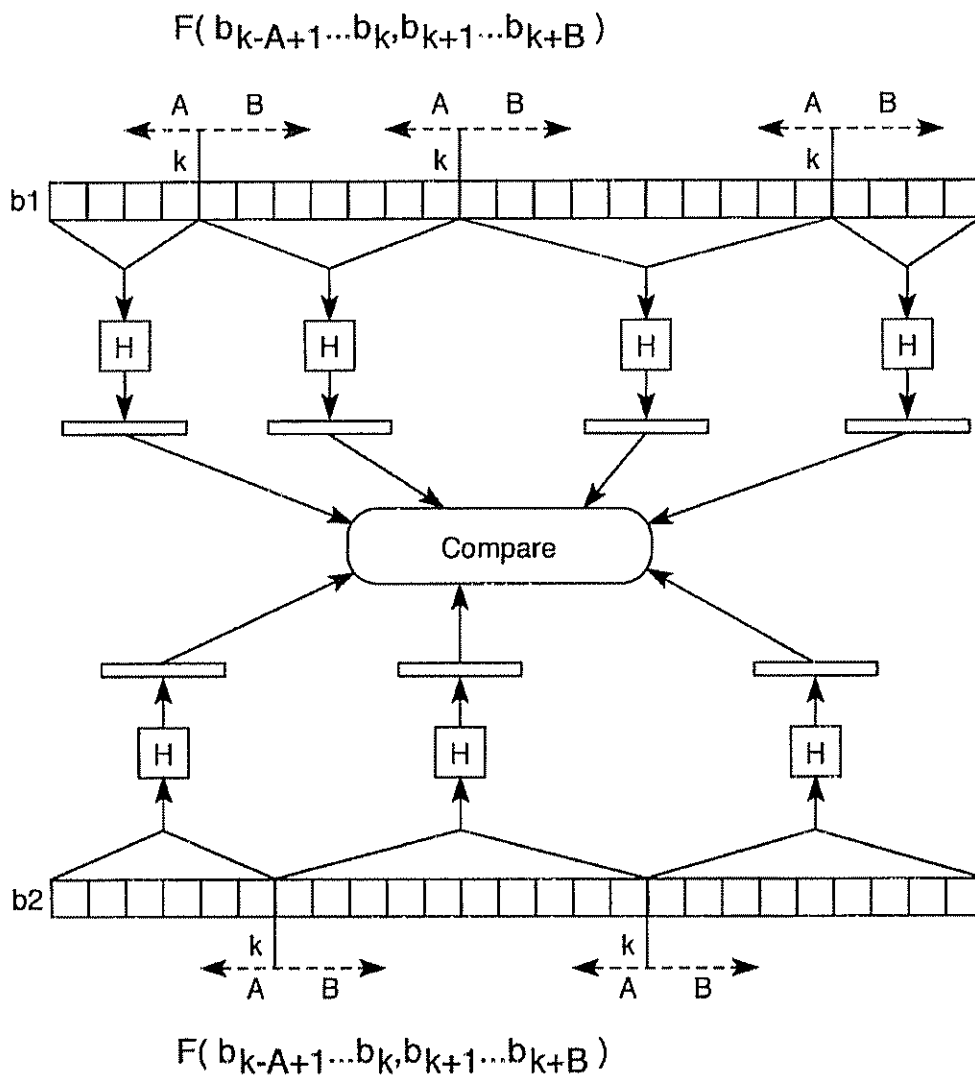


Figure 13

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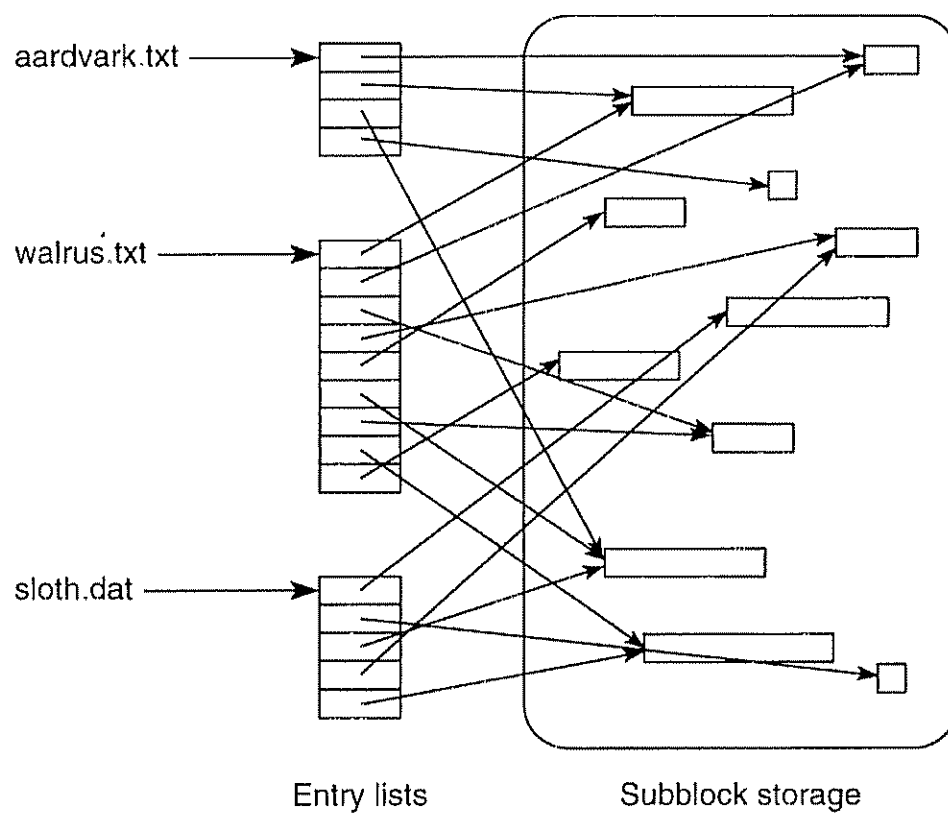


Figure 14

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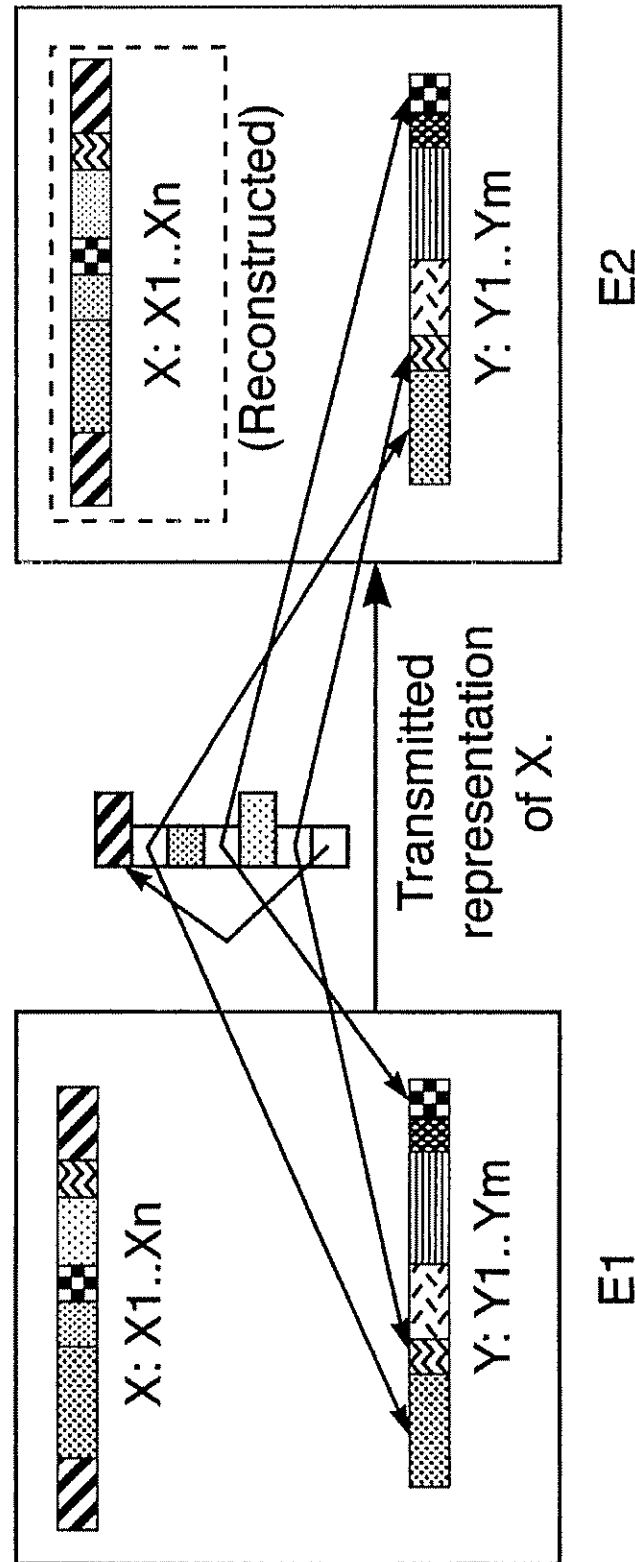


Figure 15

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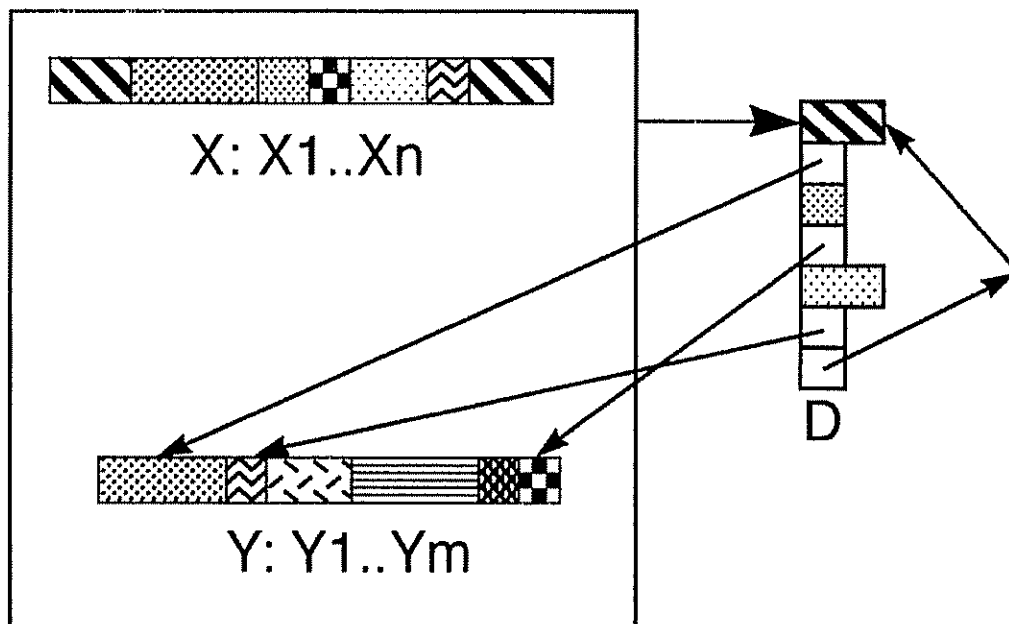


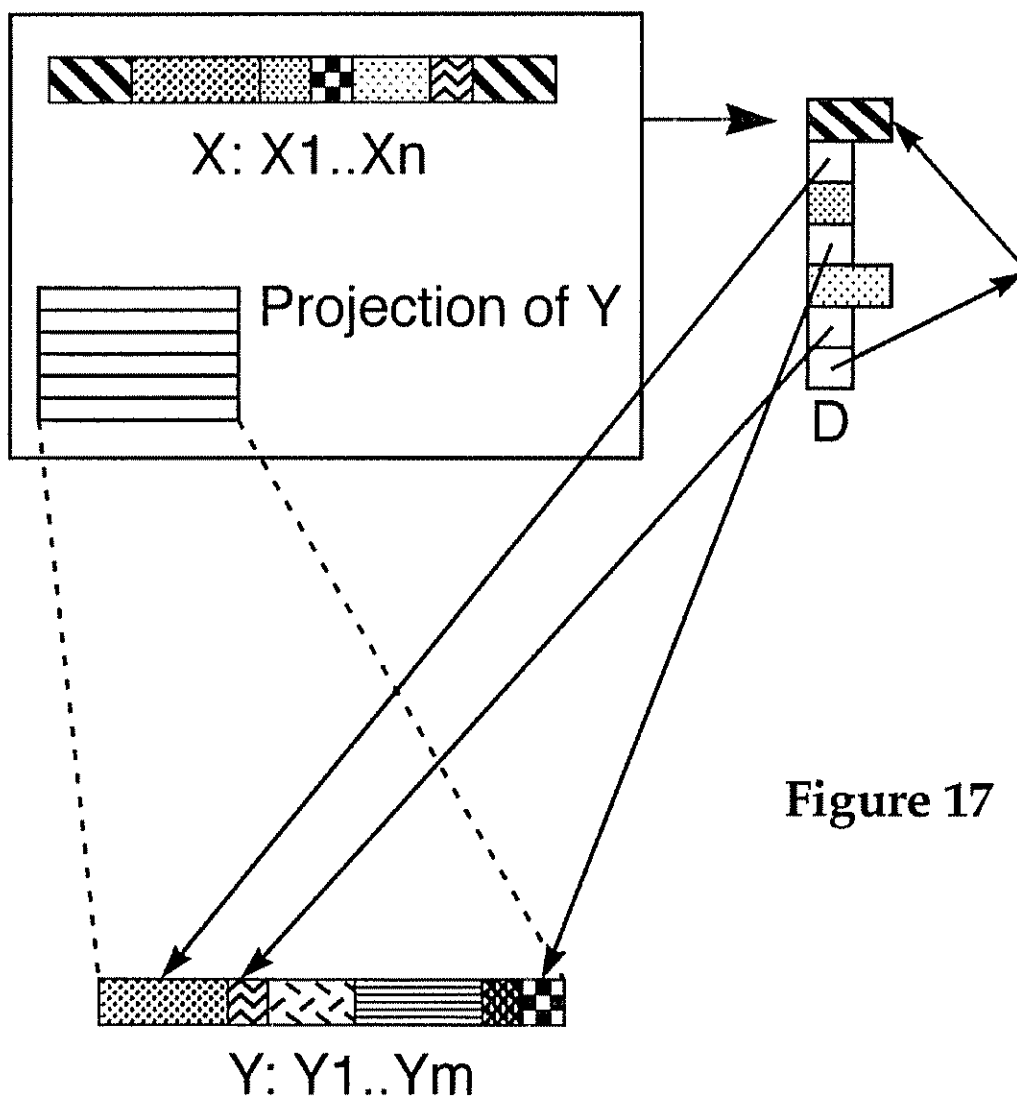
Figure 16

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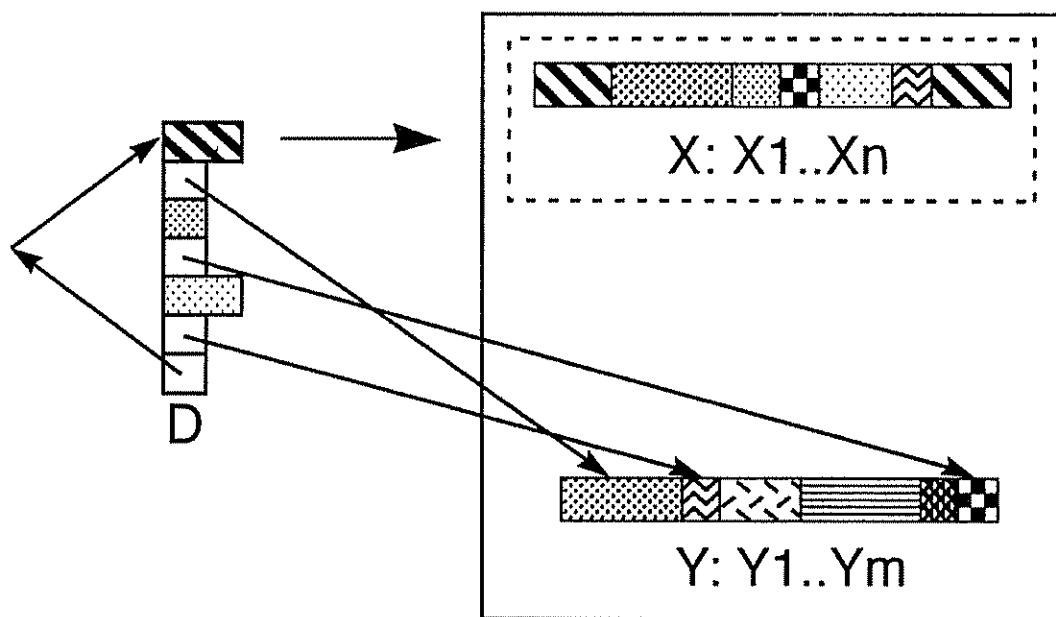


Figure 18

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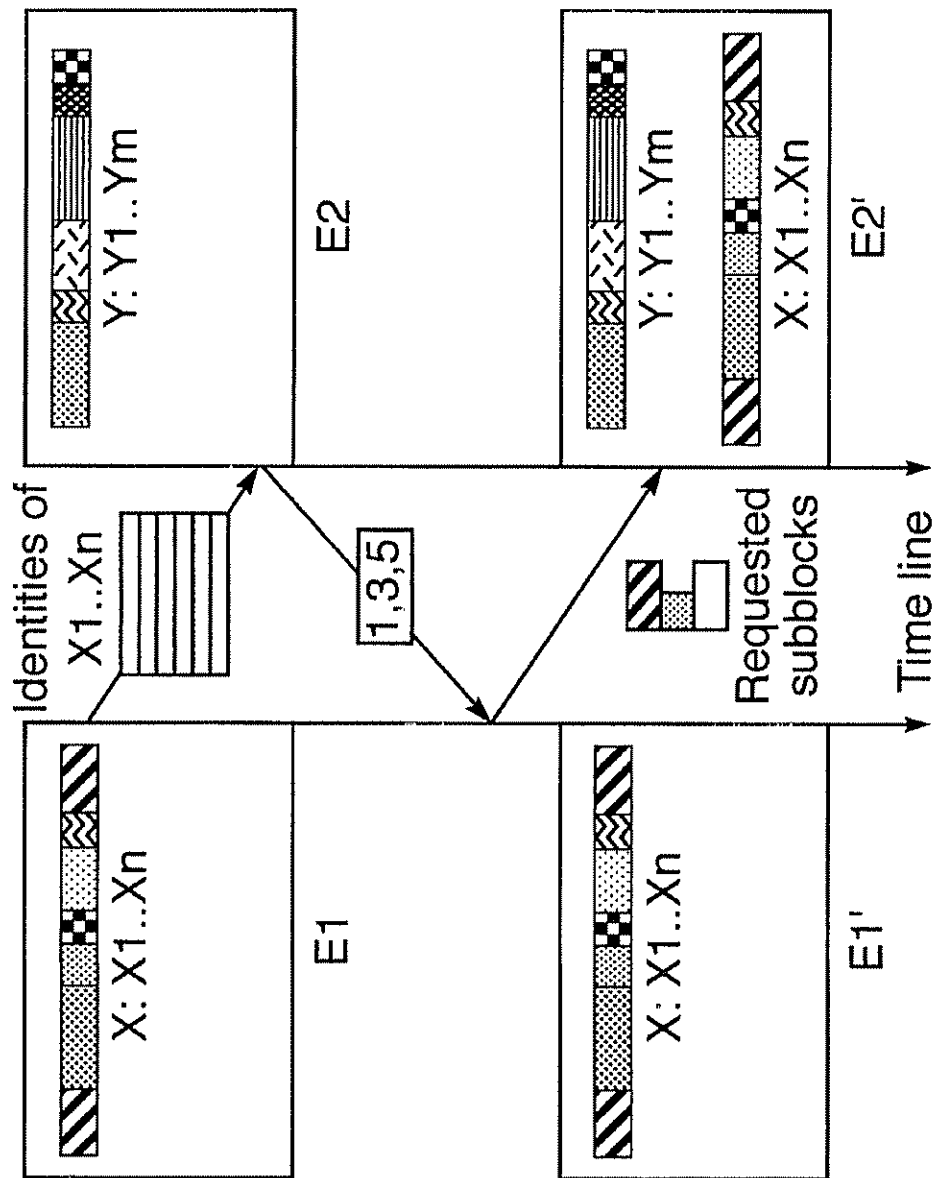


Figure 19

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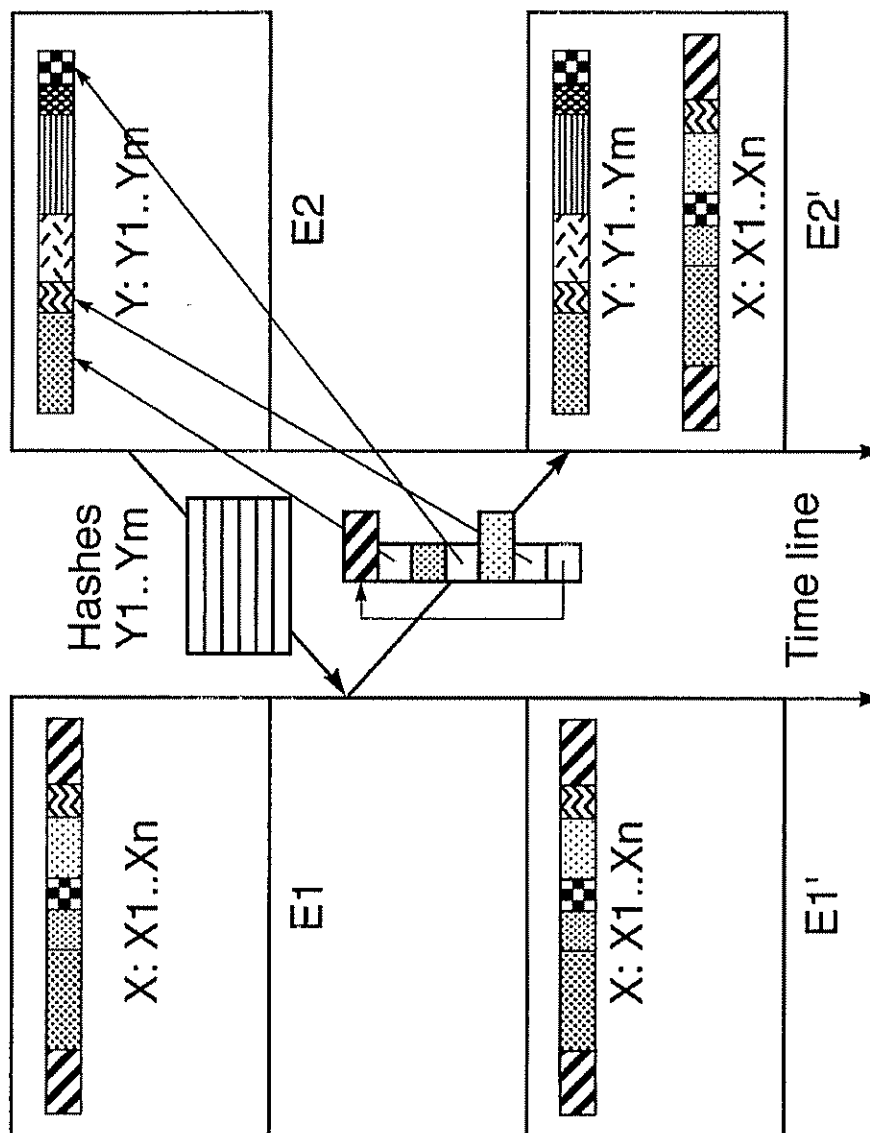


Figure 20

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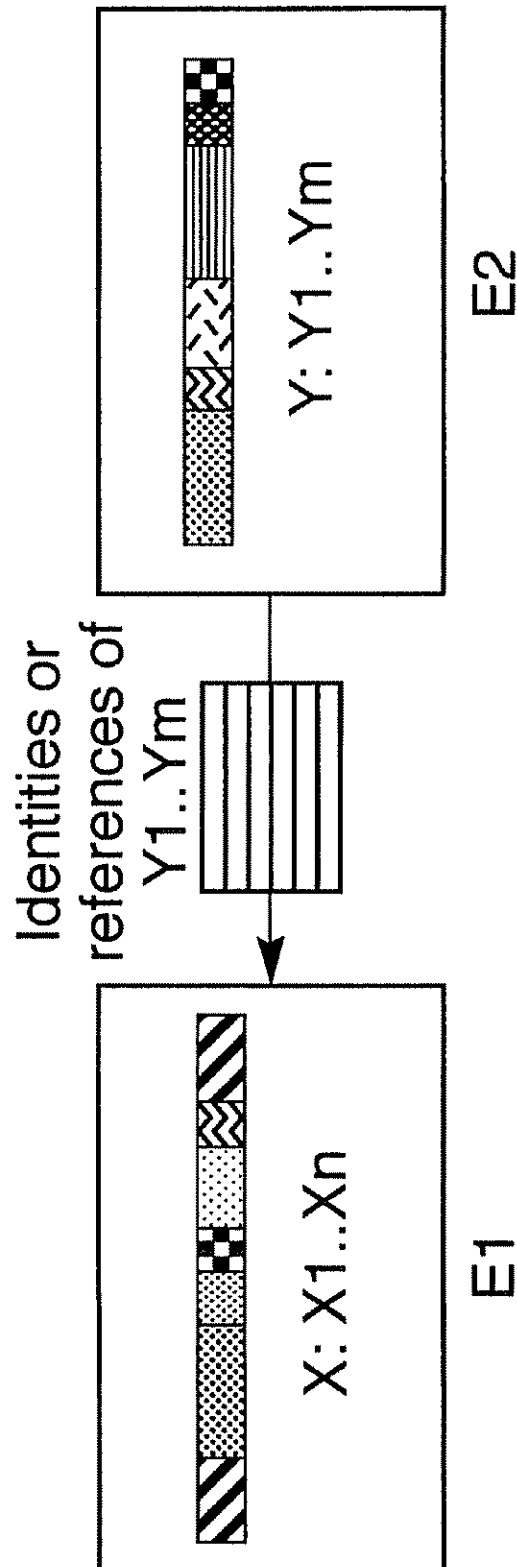


Figure 21

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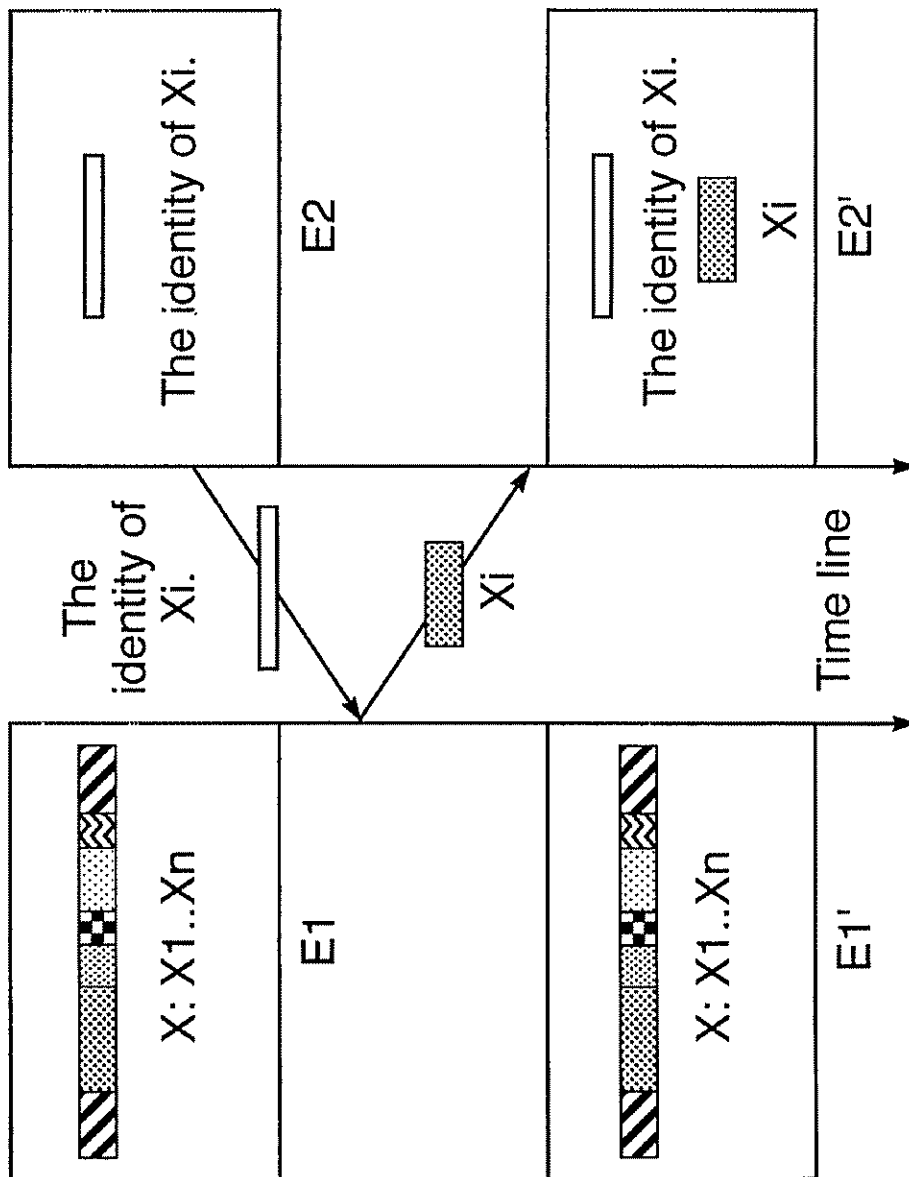


Figure 22

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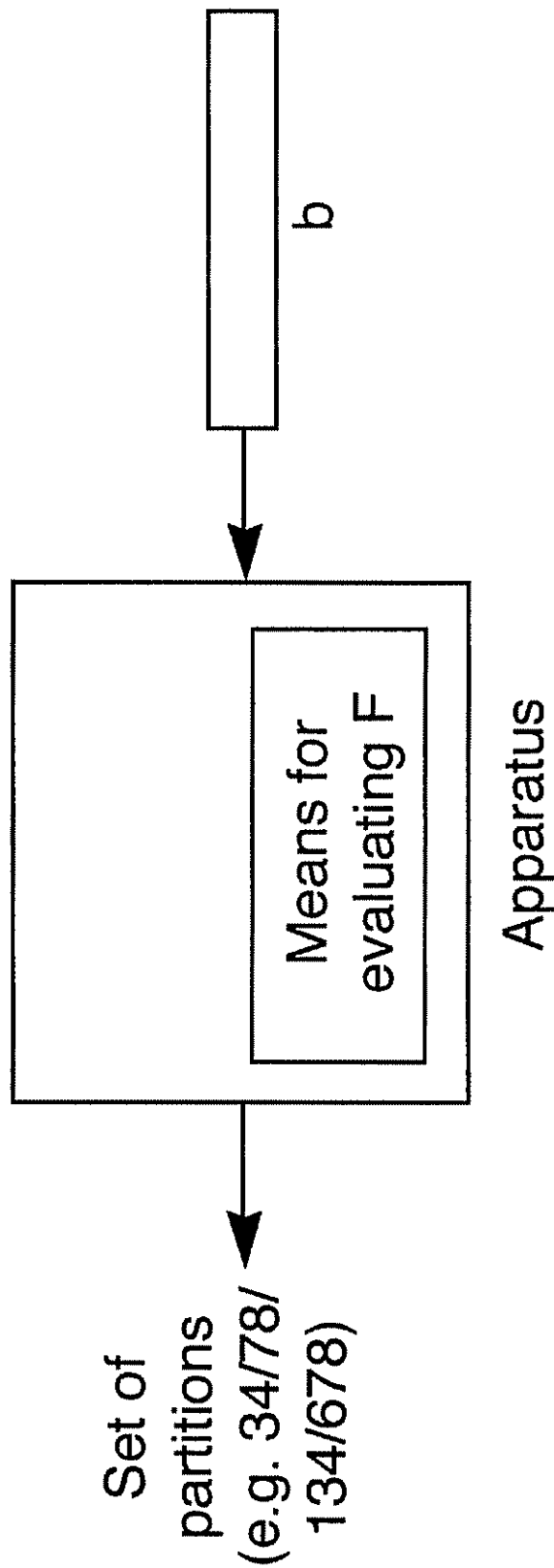


Figure 23

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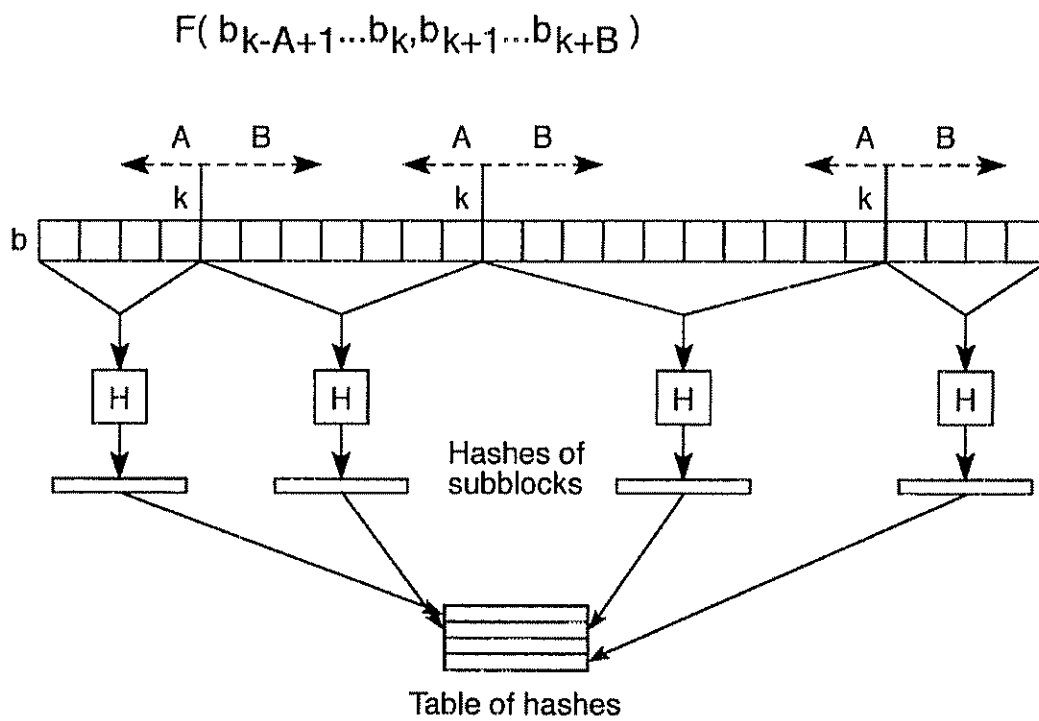


Figure 24

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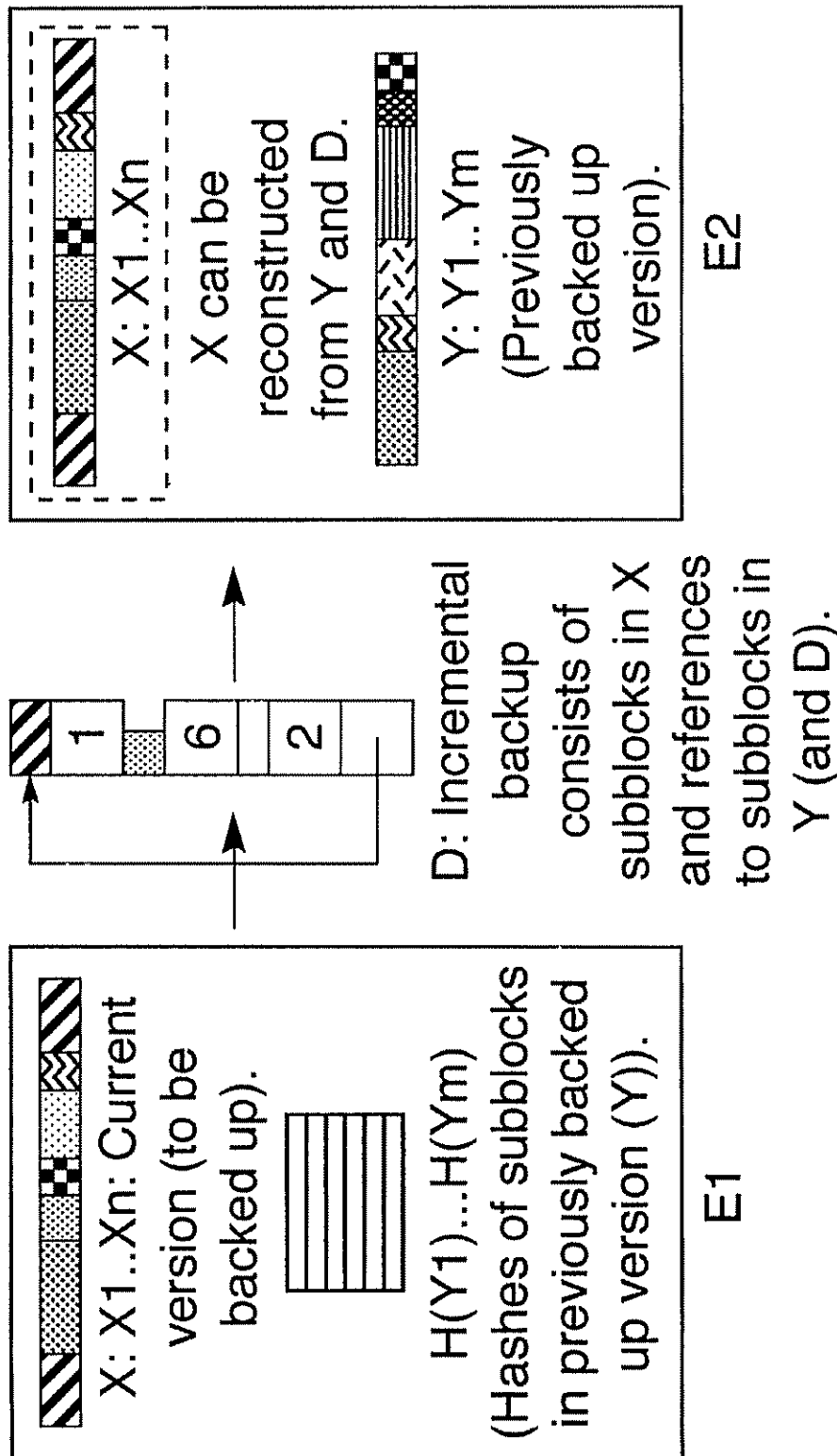


Figure 25

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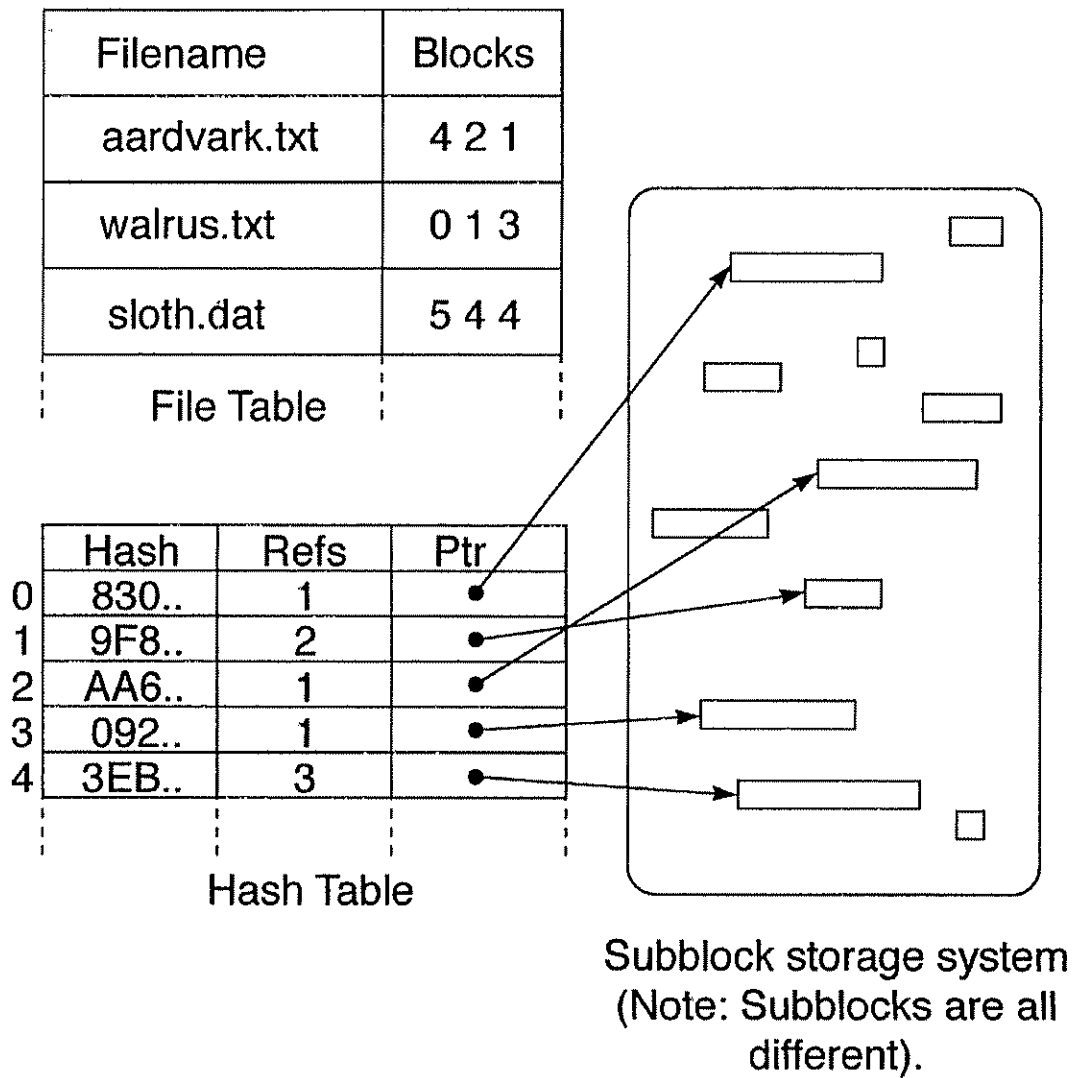


Figure 26

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1

METHOD FOR PARTITIONING A BLOCK OF DATA INTO SUBBLOCKS AND FOR STORING AND COMMUNICATING SUCH SUBBLOCKS

INTRODUCTION

The present invention provides a method and apparatus for partitioning one or more blocks of data into subblocks for the purpose of communicating and storing such subblocks in an efficient manner.

BACKGROUND

Much of the voluminous amount of information stored, communicated, and manipulated by modern computer systems is duplicated within the same or a related computer system. It is commonplace, for example, for computers to store many slightly differing versions of the same document. It is also commonplace for data transmitted during a backup operation to be almost identical to the data transmitted during the previous backup operation. Computer networks also must repeatedly carry the same or similar data in accordance the requirements of their users.

Despite the obvious benefits that would flow from a reduction in the redundancy of communicated and stored data, few computer systems perform any such optimization. Some instances can be found at the application level, one example being the class of incremental backup utilities that save only those files that have changed since the most recent backup. However, even these utilities do not attempt to exploit the significant similarities between old and new versions of files, and between files sharing other close semantic ties. This kind of redundancy can be approached only by analysing the contents of the files.

The present invention addresses the potential for reducing redundancy by providing an efficient method for identifying identical portions of data within a group of blocks of data, and for using this identification to increase the efficiency of systems that store and communicate data.

SUMMARY OF THE INVENTION

To identify identical portions of data within a group of blocks of data, the blocks must be analysed. One simple approach is to divide the blocks into fixed-length (e.g. 512-byte) subblocks and compare these with each other so as to identify all identical subblocks. This knowledge can be used to manage the blocks in more efficient ways.

Unfortunately, the partitioning of blocks into fixed-length subblocks does not always provide a suitable framework for the recognition of duplicated portions of data, as identical portions of data can occur in different sizes and places within a group of blocks of data. FIG. 1 shows how division into fixed-size subblocks of two blocks (whose only difference is the insertion of a single byte ('X')) fails to generate identical subblocks. A comparison of the two groups of subblocks would reveal no identical pairs of subblocks even though the two original blocks differ by just one character.

A better approach is to partition each block using the data in the block itself to determine the position of the partitions.

In an aspect of the invention, the blocks are partitioned at boundaries determined by the content of the data itself. For example, a block could be partitioned at each point at which the preceding three bytes has to a particular constant value. FIG. 2 shows how such a data dependent partitioning could turn out, and contrasts it with a fixed-length partitioning. In FIG. 3 data independent partitioning generates seven distinct

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subblocks whereas the data-dependent partitioning generates just four, allowing much of the similarity between the two blocks to be detected.

The fact that a partitioning is data dependent does not imply that it must incorporate any knowledge of the syntax or semantics of the data. So long as the boundaries are positioned in a manner dependent on the local data content, identical subblocks are likely to be formed from identical portions of data, even if the two portions are not identically aligned relative to the start of their enclosing blocks (FIG. 3).

Once the group of blocks has been partitioned into subblocks, the resulting group of subblocks can be manipulated in a manner that exploits the occurrence of duplicate subblocks. This leads to a variety of applications, some of which are described below. However, the application of a further aspect of the invention leads to even greater benefits.

In a further aspect of the invention, the hash of one or more subblocks is calculated. The hash function can be an ordinary hash function or one providing cryptographic strength. The hash function maps each subblock into a small tractable value (e.g. 128 bits) that provides an identity of the subblock. These hashes can usually be manipulated more efficiently than their corresponding subblocks.

Some applications of aspects of this invention are:

Fine-grained incremental backups: Conventional incremental backup technology uses the file as the unit of backup. However, in practice many large files change only slightly, resulting in a wasteful re-transmission of changed files. By storing the hashes of subblocks of the previous versions of files, the transmission of unchanged subblocks can be eliminated.

Communications: By providing a framework for communicating the hashes of subblocks, the invention can eliminate the transmission of subblocks already possessed by the receiver.

Differences: The invention could be used as the basis of a program that determines the areas of similarity and difference between two blocks.

Low-redundancy file system: Data stored in a file system can be partitioned into subblocks whose hashes can be compared so as to eliminate the redundant storage of identical subblocks.

Virtual memory: Virtual memory could be organized by subblock using a table of hashes to determine if a subblock is somewhere in memory.

Clarification of Terms

The term block and subblock both refer, without limitation, to finite blocks or infinite blocks (sometimes called streams) of zero or more bits or bytes of digital data. Although the two different terms ("blocks" and "subblock") essentially describe the same substance (digital data), the two different terms have been employed in this specification to indicate the role that a particular piece of data is playing. The term "block" is usually used to refer to raw data to be manipulated by aspects of the invention. The term "subblock" is usually used to refer to a part of a block. "Blocks" are "partitioned" into "subblocks".

The term partition has its usual meaning of exhaustively dividing an entity into mutually exclusive parts. However, within this specification, the term also includes cases where:

Not all of the block is subdivided

Multiple overlapping subblocks are formed

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A natural number is a non-negative integer (0, 1, 2, 3, 4, 5, ...)

Where the phrase zero or more is used, this phrase is intended to encompass the degenerate case where the objects being enumerated are not considered at all, as well as the case where zero or more objects are used

BRIEF DESCRIPTION

The following aspects of this invention are numbered for reference purposes. The terms "block" and "subblock" refer to blocks and subblocks of digital data.

1. In an aspect of the invention, the invention provides a method for organizing a block b of digital data for the purpose of storage, communication, or comparison, by partitioning said block into subblocks at one or more positions $k|k+1$ within said block for which $b[k-A+1 \dots k+B]$ satisfies a predetermine constraint, where A and B are natural numbers.

Note: The specification of this aspect encompasses the degenerate case in which either A or B is zero. The specification also includes the case where the constraint does not pay attention to some parts of $b[k-A+1 \dots k+B]$. For example, a constraint that pays attention only to (say) $b[k-3]$ and $b[k+2]$ would fall under the classes of constraint corresponding to $A \geq 4$ and $B \geq 2$.

2. In a further aspect of the invention, the invention provides a method according to aspect 1 in which the constraint comprises the hash of some or all of $b[k-A+1 \dots k+B]$.

3. In a further aspect of the invention, the invention provides a method according to aspect 1, for locating the nearest subblock boundary on a side of a position $p|p+1$ within a said block, comprising the step of:

a. Evaluating whether said predetermined constraint is satisfied at each position $k|k+1$, for increasing (or decreasing) k , where k starts with the value p .

4. In a further aspect of the invention, the invention provides a method according to aspect 1, wherein one or more bounds are imposed on the size of one or more subblocks.

5. In a further aspect of the invention, the invention provides a method according to aspect 1, wherein additional subblocks are formed from one or more groups of subblocks.

6. In a further aspect of the invention, the invention provides a method according to aspect 1, wherein an additional hierarchy of subblocks is formed from one or more groups of contiguous subblocks.

7. In a further aspect of the invention, the invention provides a method according to one of aspects 1 to 6, comprising the further step of:

b. Calculating the hash of each of one or more of said subblocks.

Note: The resulting collection of hashes is particularly useful if H is a strong one-way hash function.

8. In a further aspect of the invention, the invention provides a method according to one of aspects 1 to 6, comprising the further step of:

b. Forming a projection of said block, being an ordered or unordered collection of elements, wherein each element consists of a subblock, an identity of a subblock, or a reference of a subblock.

Note: The specification of this aspect is intended to admit collections that contain a mixture of various kinds of identities and references.

Note: In most applications, the output of this aspect will be an ordered list of hashes of the subblocks of the block.

9. In a further aspect of the invention, the invention provides a method for comparing one or more blocks, comprising the steps of:

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a. Partitioning one or more of said blocks into one or more subblocks in accordance with one of aspects 1 to 6.

b. Forming a projection of each said block, being an ordered or unordered collection of elements, wherein each element consists of a subblock, an identity of a subblock, or a reference of a subblock.

c. Comparing the elements of said projections of said blocks.

10. In a further aspect of the invention, the invention provides a method for representing one or more blocks, comprising:

(i) A collection of subblocks;

(ii) Block representatives (e.g. filenames) which are mapped to lists of entries that identify subblocks; whereby the modification of one of said blocks involves the following steps:

a. Partitioning some or all of said modified block into subblocks in accordance with one of aspects 1 to 6;

b. Adding to said collection of subblocks zero or more subblocks that are not already in said collection, and updating said subblock list associated with said modified block.

11. In a further aspect of the invention, the invention provides a method according to aspect 10, in which step b is replaced by:

b. Removing from said collection of subblocks zero or more subblocks, and updating said subblock list associated with said modified block.

12. In a further aspect of the invention, the invention provides a method according to aspect 10, in which step b is replaced by:

b. Adding to said collection of subblocks zero or more subblocks that are not already in the collection, removing from said collection of subblocks zero or more subblocks, and updating said subblock list associated with said modified block.

13. In a further aspect of the invention, the invention provides a method for an entity $E1$ to communicate a block X to $E1$ where $E1$ possesses the knowledge that $E2$ possesses a group Y of subblocks $Y_1 \dots Y_m$, comprising the following steps:

a. Partitioning X into subblocks $X_1 \dots X_n$ in accordance with one of aspects 1 to 6;

b. Transmitting from $E1$ to $E2$ the contents of zero or more subblocks in X , and the remaining subblocks as references to subblocks in $Y_1 \dots Y_m$ and to subblocks already transmitted.

Note: In most implementations of this aspect, the subblocks whose contents are transmitted will be those in X that are not in Y , and for which no identical subblock has previously been transmitted.

Note: To possess knowledge that $E2$ possesses $Y_1 \dots Y_m$, $E1$ need not actually possess $Y_1 \dots Y_m$ itself. $E1$ need only possess the identities of $Y_1 \dots Y_m$ (e.g. the hashes of each subblock $Y_1 \dots Y_m$). This specification is intended to admit any other representation in which $E1$ may have the knowledge that $E2$ possesses (or has access to) $Y_1 \dots Y_m$. In particular, the knowledge may take the form of a projection of Y .

Note: It is implicit in this aspect the $E1$ will be able to use comparison (or other methods) to use its knowledge of $E2$'s possession of Y to determine the set of subblocks that are common to both X and Y . For example, if $E1$ possessed the hashes of the subblocks of Y , it could compare them to the hashes of the subblocks of X to determine the subblocks common to both X and Y . Subblocks that are not common can be transmitted explicitly. Subblocks that are common to both X and Y can be transmitted by transmitting a reference to the subblock.

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14. In a further aspect of the invention, the invention provides a method for an entity E1 to communicate one or more subblocks of a group X of subblocks $X_1 \dots X_n$ to E2 where E1 possesses the knowledge that E2 possesses the blocks Y, comprising the following steps:

a Partitioning Y into subblocks $Y_1 \dots Y_m$ in accordance with one or aspects 1 to 6;

b Transmitting from E1 to E2 the contents of zero or more subblocks in X, and the remaining subblocks as references to subblocks in Y and to subblocks already transmitted

15 In a further aspect of the invention, the invention provides a method for an entity E1 to communicate a block X to E2 where E1 possesses the knowledge that E2 possesses block Y, comprising the following steps:

a Partitioning in accordance with one of aspects 1 to 6, X into subblocks $X_1 \dots X_n$ and Y into subblocks $Y_1 \dots Y_m$;

b Transmitting from E1 to E2 the contents of subblocks in X, and the remaining subblocks as references to subblocks in Y and to subblocks already transmitted.

16 In a further aspect of the invention, the invention provides a method for constructing a block D from a block X and a group Y of subblocks $Y_1 \dots Y_m$ such that X can be constructed from Y and D, comprising the following steps:

a Partitioning X into subblocks $X_1 \dots X_n$ in accordance with one of aspects 1 to 6;

b Constructing D from one or more of the following: the contents of zero or more subblocks in X, references to zero or more subblocks in Y, and references to zero or more subblocks in D.

Note: Step b above is intended to encompass the case where a mixture of the elements it describes is used.

17 In a further aspect of the invention, the invention provides a method for constructing a block D from a group X of subblocks $X_1 \dots X_n$ and a block Y such that X can be constructed from Y and D, comprising the following steps:

a Partitioning Y into subblocks $Y_1 \dots Y_m$ in accordance with one of aspects 1 to 6;

b Constructing D from one or more of the following: the contents of zero or more subblocks in X, references to zero or more subblocks in Y, and references to zero or more subblocks in D.

18 In a further aspect of the invention, the invention provides a method for constructing a block D from a block X and a block Y such that X can be constructed from Y and D, comprising the following steps:

a Partitioning in accordance with one of aspects 1 to 6, X into subblocks $X_1 \dots X_n$ and Y into subblocks $Y_1 \dots Y_m$;

b Constructing D from one or more of the following: the contents of zero or more subblocks in X, references to zero or more subblocks in Y, and references to zero or more subblocks in D.

19 In a further aspect of the invention, the invention provides a method for constructing a block D from a block X and a projection of Y, said projection comprising an ordered or unordered collection of elements wherein each element consists of a subblock in Y, an identity of a subblock in Y, or a reference of a subblock in Y, such that X can be constructed from Y and D, comprising the following steps:

a Partitioning X into subblocks $X_1 \dots X_n$ in accordance with one of aspects 1 to 6;

b Constructing D from one or more of the following: the contents of zero or more subblocks in X, references to zero or more subblocks in Y, and references to zero or more subblocks in D.

20 In a further aspect of the invention, the invention provides a method for constructing a block X from a block Y and a block D, comprising the following steps:

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a Partitioning Y into subblocks $Y_1 \dots Y_m$ in accordance with one or aspects 1 to 6;

b Constructing X from D and Y by constructing the subblocks of X based on one or more of:

(i) subblocks contained within D;

(ii) references in D to subblocks in Y;

(iii) references in D to subblocks in D;

21 In a further aspect of the invention, the invention provides a method for constructing a group X of subblocks $X_1 \dots X_n$ from a block Y and a block D, comprising the following steps:

a Partitioning Y into subblocks $Y_1 \dots Y_m$ in accordance with one of aspects 1 to 6;

b Constructing $X_1 \dots X_n$ from D and Y based on one or more of:

(i) subblocks contained within D;

(ii) references in D to subblocks in Y;

(iii) references in D to subblocks in D;

22 In a further aspect of the invention, the invention provides a method for communicating a data block X from one entity E1 to another entity E2 comprising the following steps:

a Partitioning X into subblocks $X_1 \dots X_n$ in accordance with one of aspects 1 to 6;

b Transmitting from E1 to E2 an identity of one or more subblocks;

c Transmitting from E2 to E1 information communicating the presence or absence of subblocks at E2;

d Transmitting from E1 to E2 at least the subblocks identified in step (c) as not being present at E2.

Note: The information communicated in step (c) could take the form of a bitmap (or a compressed bitmap) corresponding to the subblocks referred to in step (a). It could also take many other forms.

Note: If a group of subblocks are to be transmitted, the above steps could be performed completely for each subblock before moving onto the next subblock. The steps could be applied to any subgroup of subblocks.

23 In a further aspect of the invention, the invention provides a method for communicating a block X from one entity E1 to another entity E2, comprising the following steps:

a Partitioning X into subblocks $X_1 \dots X_n$ in accordance with one of aspects 1 to 6;

b Transmitting from E2 to E1 information communicating the presence or absence at E2 of members of a group Y or subblocks $Y_1 \dots Y_m$;

c Transmitting from E1 to E2 the contents of zero or more subblocks in X, and the remaining subblocks as references to subblocks in $Y_1 \dots Y_m$ and to subblocks transmitted.

24 In a further aspect of the invention, the invention provides a method for an entity E2 to communicate to an entity E1 the fact that E2 possesses a block Y, comprising the following steps:

a Partitioning Y into subblocks $Y_1 \dots Y_m$ in accordance with one or aspects 1 to 6;

b Transmitting from E2 to E1 references of the subblocks $Y_1 \dots Y_m$.

25 In a further aspect of the invention, the invention provides a method for an entity E1 to communicate a subblock X_i to an entity E2, comprising the following steps:

a Partitioning X into subblocks $X_1 \dots X_n$ in accordance with one of aspects 1 to 6;

b Transmitting from E2 to E1 an identity of X_i ;

c Transmitting X_i from E1 to E2.

Note: This aspect applies (among other applications) to the case of a network server E1 that serves subblocks to clients such as E2, given the identities (e.g. hashes) of the requested subblocks.

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26 In a further aspect of the invention, the invention provides a method according to one of aspects 1 to 6, wherein said subblocks are compared by comparing the hashes of said subblocks

27 In a further aspect of the invention, the invention provides a method according to one of aspects 1 to 6, wherein subsets of identical subblocks within a group of one or more subblocks are found, by inserting each subblock, an identity of each subblock, a reference of each subblock, or a hash of each subblock, into a data structure.

28 In further aspect of the invention, the invention provides an apparatus for organizing a block b of digital data for the purpose of storage, communication, or comparison, by partitioning said block into subblocks at one or more positions $k|k+1$ within said block for which $b[k-A+1 \dots k+B]$ satisfies a predetermined constraint, where A and B are natural numbers

Note: The specification of this aspect encompasses the degenerate case in which either A or B is zero. The specification also includes the case where the constraint does not pay attention to some parts of $b[k-A+1 \dots k+B]$. For example, a constraint that pays attention only to (say) $b[k-3]$ and $b[k+2]$ would fall under the classes of constraint corresponding to $A \geq 4$ and $B \geq 2$.

29 In a further aspect of the invention, the invention provides an apparatus according to aspect 28 in which the constraint comprises the hash of some or all of $b[k-A+1 \dots k+B]$

30 In a further aspect of the invention, the invention provides an apparatus according to aspect 28, for locating the nearest subblock boundary on a side of a position $p|p+1$ within a said block, comprising the step of:

a Evaluating whether said predetermined constraint is satisfied at each position $k|k+1$, for increasing (or decreasing) k , where k starts with the value p

BRIEF DESCRIPTION OF FIGURES

FIG. 1 shows how data can become "misaligned" relative to its containing blocks when data is inserted

FIG. 2 shows how data can be divided into fixed-width subblocks or variable-width subblocks

FIG. 3 shows how data-dependent partition move with the data when the data is shifted (e.g. by an insertion) H

FIG. 4 depicts the data-dependent partitioning of a block b of data into subblocks using a constraint F

FIG. 5 depicts the search within a block b for a subblock boundary using a constraint F

FIG. 6 shows how a block may be subdivided in different ways using different partitioning constraints

FIG. 7 shows how "higher order" subblocks can be constructed from one or more initial subblocks

FIG. 8 shows how different partitioning functions can produce subblocks of differing average sizes

FIG. 9 shows how subblocks can be organized into a hierarchy. Such a hierarchy can be constructed by progressively restricting a constraint F

FIG. 10 depicts a method (and apparatus) for the partitioning of a block b into subblocks using a constraint F , and the calculation of the hashes of the subblocks using hash function H

FIG. 11 depicts the partitioning of a block b into subblocks using a constraint F , and the projection of those subblocks into a structure consisting of subblock hashes, subblock data, and subblock references

FIG. 12 depicts a method (and apparatus) for partitioning two blocks $b1$ and $b2$ into subblocks, using a constraint F , and then comparing the subblocks.

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FIG. 13 depicts a method (and apparatus) for the partitioning using a constraint F , of two blocks $b1$ and $b2$ into subblocks, the calculation of the hashes of the subblocks using H , and the comparison of those hashes with each other to determine (among other things) subblocks common to both $b1$ and $b2$

FIG. 14 depicts a method (and apparatus) for a file system that employs an aspect of the invention to eliminate the multiple storage of subblocks common to more than one file (or to different parts of the same file)

FIG. 15 depicts a method (and apparatus) for the communication of a block X from $E1$ to $E2$ where both $E1$ and $E2$ possess Y

FIG. 16 depicts a method (and apparatus) for the construction of a block D from which X may be later reconstructed, given Y

FIG. 17 depicts a method (and apparatus) for the construction of a block D from which X may be later reconstructed, given Y . In this case, the entity constructing D does not have access to Y , only to a projection of Y (being perhaps the hashes of the subblocks of Y)

FIG. 18 depicts a method (and apparatus) for the reconstruction of X from the blocks Y and D

FIG. 19 depicts a method (and apparatus ($E1$ and $E2$ at each time)) for the communication of a block X from entity $E2$ where $E2$ already possesses Y

FIG. 20 depicts a method (and apparatus ($E1$ and $E2$ at each time)) for the communication of a block X from entity $E1$ to entity $E2$ where $E2$ already possesses Y and where $E2$ first discloses to $E1$ information about Y

FIG. 21 depicts a method (and apparatus) for the communication, from entity $E2$ to entity $E1$, information about a block (or group of subblocks) Y at $E2$

FIG. 22 depicts a method (and apparatus ($E1$ and $E2$ at each time)) for the communication from entity $E1$ to entity $E2$ of subblock X_i following a request by entity $E2$ for the subblock X_i

FIG. 23 depicts an apparatus for partitioning a block b (the input) using a constraint F . The output is a set of subblock boundary positions.

FIG. 24 depicts a method (and apparatus) for the partitioning of a block b into subblocks using constraint F , and the projection of those subblocks into a table of subblock hashes.

FIG. 25 depicts a method (and apparatus) for the transmission from entity $E1$ to $E2$ of a block X where $E2$ possesses Y and $E1$ possesses a table of the hashes of the subblocks of Y (a projection of Y)

FIG. 26 depicts a method (and apparatus) for a file system that employs an aspect of the invention to eliminate the multiple storage of data common to more than file (or to different parts of the same file)

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

This section contains a detailed discussion of mechanisms that could be used to implement aspects of the invention. It also contains examples of implementations of selected aspects of the invention. However, nothing in this section should be interpreted as a limitation on the scope of this patent.

Units of Information

Aspects of this invention can be applied at various levels of granularity of data. For example, if the data was treated

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as a stream of bits, boundaries could be placed between any two bits. However, if the data was treated as a stream of bytes, boundaries would usually be positioned only between bytes. The invention could be applied with any unit of data, and in this document references to bits and bytes should usually be interpreted as admitting any granularity.

The Concept of Entity

At various places, this patent specification uses the term "entity" to describe an agent. This term is purposefully vague and is intended to cover all forms of agent including, but not limited to:

- Computer systems.
- Networks of computer systems.
- Processes in computer systems
- File systems.
- Components of software
- Dedicated computer systems
- Communications systems

The Concepts of Identity and Reference

This patent specification frequently refers to "identities" of subblocks and "references" to subblocks. These terms are not intended to be defined precisely.

The identity of a subblock means any piece of information that could be used in place of the subblock for the purpose of comparison for identity. Identities include, but are not limited to:

- The subblock itself
- A hash of the subblock.

The subblock acts as its own identity because subblocks themselves can be compared with each other. Hashes of subblocks also act as identities of subblocks because hashes of subblocks can be compared with each other to determine if their corresponding subblocks are identical.

A reference to a subblock means any piece of information that could be used in practice by one entity to identify to another entity (or itself) a particularly valued subblock, where the two entities may already share some knowledge. For example, the two entities might each possess the knowledge that the other entity already possesses ten subblocks of known values having particular index values numbered one to ten.

Once two entities have a basis of shared knowledge, it is possible for them to identify a subblock in ways more concise than the transmission of an identity. A reference to a particularly valued subblock can take (without limitation) the following forms:

- An identity.

- An identifying number of a subblocks possessed by the receiver.

- An identifying number of a subblock previously transmitted between the two communicants

- The location of the subblock in some shared data space.

- As relative subblocks number

- Ranges of the above.

The concept of knowledge of a subblock is related to the concepts of identity and reference. An entity may have knowledge of a subblock (or knowledge that another entity possesses a subblock) without actually possessing the subblock itself. For example, it might possess an identity of the subblock or a reference to the subblock.

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The Use of Ranges

In any situation where a group of values that have contiguous values (e.g. 6, 7, 8, 9) is to be communicated or stored, such a group can be represented using a range (e.g. 6-9) which may take up less communication time or storage space. Ranges can be applied to all kinds of things, such as index values and subblock numbers. In particular, if an entity notices that the references (to subblocks) that it is about to transmit are contiguous, it can replace the references with a range.

Ranges can be represented in any way that identifies the first and last element of the range. Three common representations are:

- The first and last element of the range.

- The first element and the length of the range

- The last element and the length of the range

The concept of range can be generalized to include the compression of any group of values that exhibit compressible structure.

The Use of Backward References

References can be used not only to refer to data shared by two communicants at the start of a transmission, but can also be used to refer to data communicated at some previous time during the transmission.

For example, if an entity A notices that the subblock it is about to transmit to another entity B was not possessed by B at the start of the transmission, but has since been transmitted from A to B, then A could code the second instance of the subblock as a reference to the previous instance of the subblock. The range mechanism can be used here too.

No Requirement for Subblock Framing Information

It is possible that an entity E1 could transmit a group X of subblocks $X_1 \dots X_n$ as a group to an entity E2 simply by sending the concatenation of the subblocks. There may be no need for any framing information (e.g. information at the start of each subblock giving the length of the subblock or "escape" codes to indicate subblock boundaries), as E2 is capable of partitioning X into $X_1 \dots X_n$ itself.

No Requirement for Ordering Subblocks

If two entities E1 and E2 both possess the same unordered group Y of subblocks (or knowledge of such a group of subblocks) then even though E1 and E2 may not possess the subblocks in the same order, the subblocks can still be referred to using a subblock index or serial number. This is achieved by having E1 and E2 each sort their subblocks in accordance with some mutually agreed (or universally defined) ordering method and then number the subblocks in the resultant ordered group of subblocks. These number (or ranges of such numbers) can then be used to refer to the subblocks.

An Overview of Hash Functions

Although the use of a hash function is not essential in all aspects of this invention, hash functions provide such advantages in the implementation of this invention that an overview of them is warranted.

A hash function accepts a variable-length input block of bits and generates an output block of bits that is based on the input block. Most hash functions guarantee that the output

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block will be of a particular length (e.g. 16 bits) and aspire to provide a random, but deterministic, mapping between the infinite set of input blocks and the finite set of output blocks. The property of randomness enables these outputs, called "hashes", to act as easily manipulated representatives of the original block

Hash functions come in at least four classes of strength.

Narrow hash functions: Narrow hash functions are the weakest class of hash functions and generate output values that are so narrow (e.g. 16 bits) that the entire space of output values can be searched in a reasonable amount of time. For example, an 8-bit hash function would map any data block to a hash in the range 0 to 155. A 16-bit hash function would map to a hash in the range 0 to 65535. Given a particular hash value, it would be possible to find a corresponding block simply by generating random blocks and feeding them into the narrow hash function until the searched-for value appeared. Narrow hash functions are usually used to arbitrarily (but deterministically) classify a set of data values into a small number of groups. As such, they are useful for constructing hash table data structures, and for detecting errors in data transmitted over noisy communication channels. Examples of this class: CRC-16, CRC-32, Fletcher checksum, the IP checksum

Wide hash functions: Wide hash functions are similar to narrow hash functions except that their output values are significantly wider. At a certain point this quantitative difference implies a qualitative difference. In a wide hash function, the output value is so wide (e.g. 128 bits) that the probability of any two randomly chosen blocks having the same hashed value is negligible (e.g. about one in 10^{38}). This property enables these wide hashes to be used as "identities" of the blocks of data from which they are calculated. For example, if entity E1 has a block of data and sends the wide hash of the block to an entity E2, then if entity E2 has a block that has the same hash, then the a-priori probability of the blocks actually being different is negligible. The only catch is that wide hash functions are not designed to be non-invertible. Thus, while the space of (say) 2^{128} values is too large to search in the manner described for narrow hash functions, it may be easy to analyse the hash function and calculate a block corresponding to a particular hash. Accordingly, E1 could fool E2 into thinking E1 had one block when it really had a different block. Examples of this class: any 128-bit CRC algorithm.

Weak one-way hash functions: Weak one-way hash functions are not only wide enough to provide "identity", but they also provide cryptographic assurance that it will be extremely difficult, given a particular hash value, to find a block corresponding to that hash value. Examples of this class: a 64-bit DES hash.

Strong one-way hash functions: Strong one-way hash functions are the same as weak one-way hash functions except that they have the additional property of providing cryptographic assurance that it is difficult to find any two different blocks that have the same hash value, where the hash value is unspecified. Examples of this class: MD4, MD5, and SHA-1.

These four classes of hash provide a range of hashing strengths from which to choose. As might be expected, the speed of a hash function decreases with strength, providing a tradeoff, and different strengths are appropriate in different applications. However, the difference is small enough to admit the use of strong one-way hash functions in all but the most time-critical applications.

The term cryptographic hash is often used to refer to hashes that provide cryptographic strength, encompassing both the

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class of weak one-way hash functions and the class of strong one-way hash functions. However, as strong one-way hash functions are almost preferable to weak one-way hash functions, the term "cryptographic hash" is used mainly to refer to the class of strong one-way hash functions.

The present invention can employ hash functions in at least two roles:

1. To determine subblock boundaries
2. To generate subblock identities.

Depending on the application, hash functions from any of the four classes above could be employed in either role. However, as the determination of subblock boundaries does not require identity or cryptographic strength, it would be inefficient to use hash functions from any but the weakest class. Similarly, the need for identity, the ever-present threat of subversion, and the minor performance penalty for strong one-way hash functions (compared to weak ones) suggests that nothing less than strong one-way hash functions should be used to calculate subblock identities.

The security dangers inherent in employing anything less than a strong one-way hash function to generate identities can be illustrated by considering a communications system or file system that incorporates the invention using any such weaker hash function. In such a system, an intruder could modify a subblock (to be manipulated by a target system) in such a way that the modified subblock has the same hash as another subblock known by the intruder to be already present in the target system. This could result in the target system retaining its existing subblock rather than replacing it by a new one. Such a weakness could be used (for example) to prevent a target system from properly applying a security patch retrieved over a network.

Thus, while wide hash functions could be safely used to calculate subblocks in systems not exposed to hostile humans, even weak one-way hash functions are likely to be insecure in those systems that are.

We now turn to the ways in which hashes of blocks or subblocks can actually be used.

The Use of Cryptographic Hashes

The theoretical properties of cryptographic hashes (and here is meant strong one-way hash functions) yield particularly interesting practical properties. Because such hashes are significantly wide, the probability of two randomly-chosen subblocks having the same hash is practically zero (for a 128-bit hash, it is about one in 10^{38}), and because it is computationally infeasible to find two subblocks having the same hash, it is practically guaranteed that no intelligent agent will be able to do so. The implication of these properties is that from a practical perspective, the finite set of hash values for a particular cryptographic hash algorithm is one-to-one with the infinite set of finite variable length subblocks. This theoretically impossible property manifests itself in practice because of the practical infeasibility of finding two subblocks that hash to the same value.

This property means that, for the purposes of comparison (or identically), cryptographic hashes may safely be used in place of the subblocks from which they were calculated. As most cryptographic hashes are only about 128 bits long, hashes provide an extremely efficient way to compare subblocks without requiring the direct comparison of the content of the subblocks themselves. Such comparisons can be used to eliminate many transmissions of information. For example, a subblock X_1 on a computer C1 in Sydney could be compared with a subblock Y_1 on a computer C2 in Boston

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by a computer C3 in Paris, with the total theoretical network traffic being just 256 bits (C1 and C2 each send the 128-bit hash of their respective subblocks to C3 for comparison, and C3 compares the two hashes)

Some of the ways in which cryptographic hashes could be used in aspects of this invention are:

Cryptographic hashes can be used to compare two subblocks without having to compare, or requiring access to, the content of the subblocks

If it is necessary to be able to determine whether a subblock T is identical to one of a group of subblocks, the subblocks themselves need not be stored, just a collection of their hashes. The hash of any candidate subblock can then be compared with the hashes in the collection to establish whether the subblock is in the group of subblocks from which the collection of hashes was generated

Cryptographic hashes can be used to ensure that the partitioning of a block into subblocks and the subsequent reassembly of the subblocks into a reconstructed block is error-free. This can be done by comparing the hash of the original block with the hash of the reconstructed block

If an entity E1 calculates the hash of a subblock X_1 and transmits it to E2, then if E2 possesses X_1 , or even just the hash of X_1 , then E2 can determine without any practical doubt that E1 possesses X_1

If an entity E1 passes a key (consisting of a block of bits) chosen at random to an entity E2, E2 may then prove to E1 that it possesses a subblock by sending E1 the hash of the concatenation of the key and the subblock. This mechanism could be used as an additional check in security applications.

If a group of subblocks must be compared so as to find all subsets of identical subblocks, the corresponding set of hashes of the subblocks may be calculated and compared instead.

Many of the uses of cryptographic hashes for subblocks can also be applied to blocks. For example, cryptographic hashes can be used to determine whether a block has changed at all since it was last backed up. Such a check could eliminate the need for further analysis.

Use of Hashes as a Safety Net

A potential disadvantage of deploying aspects of this invention is that it will add extra complexity to the systems into which it is incorporated. This increased complexity carries the potential to increase the chance of undetected failures

The main mechanism of complexity introduced by many aspects of the invention is the partitioning of blocks (e.g. files) into subblocks, and the subsequent re-assembly of such subblocks. By partitioning a block into subblocks, a system creates the potential for subblocks to be erroneously added, deleted, rearranged, substituted, duplicated, or in some other way exposed to a greater risk of accidental error

This risk can be reduced or eliminated by calculating the hash (preferably a cryptographic hash of the block before it is partitioned into subblocks, storing the hash with an entity associated with the block as a whole, and then later comparing the stored hash with a compound hash of the reconstructed block. Such a check would provide a very strong safety net that would virtually eliminate the risk of undetected errors arising from the use of this invention.

Choosing a Partitioning Constraint Function

Although the requirements for the block partitioning constraint (e.g. in the form of a constraint function F) are not

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stringent, care should be taken to select a function that suits the application to which it is to be applied

In situation where the data is highly structured and knowledge of the data is available, a choice of an F that tends to place subblock boundaries at positions in the data that correspond to obvious boundaries in the data could be advantageous. However, in general, F should be chosen from the class of narrow hash functions. Use of a narrow hash function for F provides both efficiency and a (deterministic) randomness that will enable the implementation to operate effectively over a wide-range of data.

One of the most important properties of F is the probability that F will place a boundary at any particular point when applied to completely random data. For example, a function with a probability of one would produce a boundary between each bit (or byte), whereas a function with a probability of zero would never produce any boundaries at all. In a real application, a more moderate probability would be chosen (e.g. 1/1024) so as to yield useful subblock sizes. The probability can be tuned to suit the application.

We end this section with an example of a narrow hash function that has been implemented and tested and seems to perform well on a variety of data types. The hash function calculates a hash value from three bytes.

$$H(b_1, b_2, b_3) = ((40543 \times ((b_1 \ll 8) \oplus (b_2 \ll 4) \oplus b_3)) \gg 4) \mid p$$

The following notation has been used: "x" is multiplication, "<<" is left bit shift, ">>" is right bit shift, "⊗" is exclusive or, "⌋" is modulo. The constant p is the inverse of the probability of placing a boundary at an arbitrary position in a randomly generated block of data, and can be set to any integer value in [0,65535]. However, in practice it seems to be advantageous to choose values that are prime (Mersenne primes seem to work well). The value 40543 was chosen carefully in accordance with the hash function design guidelines provided in pages 508–613 of the book:

Knuth D. E., "The Art of Computer Programming: Volume 3: Sorting and Searching", Addison Wesley, 1973

The function generates a value in the range [0, p-1] and can be used in practice by placing a boundary at each point where the preceding three bytes hash to a predetermined constant value V. This would imply that its arguments b_1, b_2, b_3 correspond to the argument A in aspect one above. To avoid pathological behaviour in the commonly occurring case of runs of zeros, it is wise to choose a non-zero value for V.

In a real implementation, p was set to 511 and V was set to one.

Placing an Upper and Lower Bound on the Subblock Size

The use of data-dependent subblock boundaries provides a way to deterministically partition similar portions of data in a context-independent way. However, if artificial bounds are not placed on the subblock size, particular kinds of data will yield subblocks that are too large or too small to be effective. For example, if a file contains a block of a million identical bytes, any deterministic constraint (that operates at the byte level) must either partition the block into one subblock or a million subblocks. Both alternatives are undesirable.

A solution to this problem is artificially to impose an upper bound U and a lower bound L on the subblock size. There seem to be a limitless number of ways of doing this. Here are some examples:

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Upper bound: Subdivide subblocks that are longer than U bytes at the points, U, 2U, 3U, and so on, where U is the chosen upperbound on subblock size

Upper bound: Subdivide subblocks that are longer than U bytes at points determined by a secondary hash function

Lower bound: Of the set of boundaries that bound subblocks less than L bytes long, remove those boundaries that are closer to their neighbouring boundaries than their neighbouring boundaries are to their neighbouring boundaries.

Lower bound: If the block is being scanned sequentially, do not place a boundary unless at least L bytes have been scanned since the previous boundary.

Lower bound: Of the set of boundaries that bound subblocks less than L bytes long, remove those boundaries that satisfy some secondary hash function

Lower bound: Of the set of boundaries that bound subblocks less than L bytes long, remove randomly chosen boundaries until all the resulting subblocks are at least L bytes long

Many other such schemes could be devised

The Use of Multiple Partitionings

In most applications the use of just one partitioning into subblocks will be sufficient. However, in some applications there may be a need for more than one subblock partitioning. For example, in applications where channel space is expensive, it may be appropriate to partition each block of data in W different ways, using W different constraint functions $F_1 \dots F_W$ where each function provides a different average subblock size. For example, four different partitions could be performed using functions that provide subblocks of average length 256 bytes, 1K, 10K, and 100K. By providing a range of different sizes of subblocks to choose from, such as organization could simultaneously indicate large blocks extremely efficiently, while still retaining fine-grained subblocks so that minor changes to the data do not result in voluminous updates (FIG. 8).

The efficiency of such a scheme could be improved by performing the partitioning all in one operation using increasing constraints on a single F. For example, one could use the example hash function described earlier, but use different values of the constant p to determine the different levels of subdivision. By choosing appropriately related values of p, the set of boundaries that could be produced by the different F could be arranged to be subsets of each other, resulting in a tree structure of subblocks. For example, values of p of 32, 64, and 128, and 256 could be used. FIG. 9 shows how the subblocks of four levels of the tree could relate to each other.

A further method could define the hash of a larger block to be the hash of the hashes of its component blocks.

Multiple partitionings could also be useful simply to provide a wider pool of subblocks to compare. For example, it may be appropriate to partition each block of data in W different ways using W different functions $F_1 \dots F_W$ where each function yields roughly the same subblock sizes, but at different positions within the block.

Another technique would be to create an additional set of boundaries based on the boundaries provided by a hash function. For example, a fractal algorithm could be used to partition a block based upon some other partitioning provided by a function F.

Comparing Subblocks

In most applications of this invention, there will be a need at some stage to identify identical subblocks. This can be done in a variety of ways:

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Compare the subblocks themselves

Compare the hashes of the subblocks

Compare identifies of the subblocks

Compare references to the subblocks

In most cases, the problem reduces to that of taking a group of subblocks of data and finding all subsets of identical subblocks. This is a well-solved problem and discussion of various solutions can be found in the following books:

Knuth D. E., "The Art of Computer Programming: Volume 1: Fundamental Algorithms". Addison Wesley, 1973

Knuth D. E., "The Art of Computer Programming: Volume 3: Sorting and Searching", Addison Wesley, 1973

In most cases, the problem is best solved by creating a data structure that maintains the subblocks, or references to the subblocks, in sorted order, and then inserts each subblock one at a time into the data structure. Not only does this identify all currently identical subblocks, but it also establishes a structure that can be used to determine quickly whether incoming subblocks are identical to any of those already held. The following data structures are described in the books referenced above and provide just a sample of the structures that could be used:

Hash tables.

Sorted trees (binary, N-ary, AVL).

Sorted linked lists

Sorted arrays.

Of the multitude of solutions to the problem of matching blocks of data, one solution is worthy of special attention: the hash table. Hash tables consist of a (usually) finite array of slots into which values may be inserted. To add a value to a hash table, the value is hashed (using a hash function that is usually selected from the class of narrow hash functions) into a slot number, and the value is inserted into that slot. Later, the value can be retrieved in the same manner. Provisions must be made for the case where two data values, to be stored in the same table, hash to the same slot number.

Hash tables are likely to be of particular value in the implementation of this invention because:

They provide very fast (essentially constant time) access.

Many applications will need to calculate a strong one-way hash of each subblock, and a portion of this value can be used to index the hash table.

Particularly effective would be a hash table indexed by a portion of a strong one-way hash of the subblocks it stores, with each table entry containing (a) the strong one-way hash of the subblock, and (b) a pointer to the subblock stored elsewhere in memory.

The Use of Compression, Encryption, and Integrity Techniques

Aspects of the invention could be enhanced by the use of data compression, data encryption, and data integrity techniques. The applications of these techniques include, but are not limited to, the following applications:

Any subblock that is transmitted or represented in its raw form could alternatively be transmitted or represented in a compressed or encrypted form.

Subblocks could be compressed and encrypted before further processing by aspects of this invention.

Blocks could be compressed and encrypted before further processing by aspects of this invention.

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Communications or representations could be compressed or encrypted

Any component could carry additional checking information such as checksums or digests of the data in the component.

Ad-hoc data compression techniques could be used to further compress references and identities or consecutive runs of references and identities

Storage of Variable-Length Subblocks on Disk

The division of data into subblocks of varying length presents some storage organization problems (if the subblocks are to be stored independently of each other), as most hardware disk systems are organized to store an array of fixed-length blocks (e.g. one million 512-byte blocks) rather than variable-length ones. Here are some techniques that could be used to tackle this problem:

Each subblock could be stored in an integral number of disk blocks, with some part of the last disk block being wasted. For randomly sized subblocks, this scheme will waste on average half a disk block per subblock.

Create a small subset of different bucket sizes (e.g. powers of two) and create arrays on the disk that pack collections of these buckets efficiently into the disk blocks. For example, if disk blocks were 512 bytes long, one could fairly efficiently pack five 200-byte buckets into an array of two disk blocks. Each subblock would be stored in the smallest bucket size that would hold the subblock, with the unused part of the bucket being wasted.

Treat the disk blocks as a vast array of bytes, and use well-established heap management techniques to manage the array. A sample of such techniques appears in pages 435–451 of the book:

Knuth D. E., "The Art of Computer Programming: Volume 1: Fundamental Algorithms", Addison Wesley, 1973

The Use of Concurrency

Two processes are said to be concurrent if their execution takes place in some sense at the same time:

In interleaving concurrency, some or all of the operations performed by the two processes are interleaved in time, but the two processes are never both executing at exactly the same instant

In genuine concurrency, some or all of the operations performed by the two processes are genuinely executed at the same instant. Implementations of the present invention could incorporate either form of concurrency to various degrees. In most of the aspects of the invention, some subset of the steps of each aspect could be performed concurrently. In particular (without limitation):

A block could be split into parts and the parts partitioned concurrently

The processing of subblocks defined during a sequential partitioning of a block need not be deferred until the entire block has been partitioned. In particular, the hashes of already-defined subblocks could be calculated and compared while further subblocks are being defined.

Communicating entities that decompose and compose blocks could execute concurrently.

Where more than one block must be partitioned for processing, such partitioning could be performed concurrently.

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Many more forms of concurrency within aspects of this invention could be identified.

Example: Partitioning a Block

We now present a simple example of how a block might be partitioned in practice. Consider the following block of bytes:

$b_1 \ b_2 \ b_3 \ b_4 \ b_5 \ b_6 \ b_7 \ b_8 \ b_9$

In this example, an example hash function H will be used to partition the block. Boundaries will be represented by pairs such as $b_4|b_7$. We will assume that H returns a boolean value based on its argument and that a boundary is to be placed at each $b_i|b_{i+1}$ for which $H(b_{i-2}, b_{i-1}, b_i)$ evaluates to true.

As the hash function accepts 3 byte arguments, we start at $b_3|b_4$ and evaluate $H(b_1, b_2, b_3)$. This turns out to be false (for the purposes of example), so we move to $b_4|b_5$ and evaluate $H(b_2, b_3, b_4)$. This turns out to be true, so a boundary is placed at $b_4|b_5$. Next, we move to $b_5|b_6$ and evaluate $H(b_3, b_4, b_5)$. This turns out to be false so we move on. $H(b_4, b_5, b_6)$ is true so we place a boundary at $b_6|b_7$. This process continues until the end of the block is reached.

$b_1 \ b_2 \ b_3 \ b_4 \ | \ b_5 \ b_6 \ | \ b_7 \ b_8 \ b_9$

Some variations on this approach are:

Imposition of a lower bound L on subblock size by skipping ahead L bytes after placing a boundary.

Imposition of an upper bound U on block size by artificially placing a boundary if U bytes have been processed since the last boundary was placed.

Improving the efficiency of the hash calculations by using some part of the calculation of the hash of the bytes at one position to calculate the hash at the next position. For example, it may be more efficient to calculate $H(x,y,z)$ if $H(*,x,y)$ has already been calculated. For example, the Internet IP checksum is organized so that a single running checksum value can be maintained, with bytes entering the window being added to the checksum, and bytes exiting the window being subtracted from the checksum.

Applying this algorithm in reverse, starting from the end of the block and working backwards.

Finding the subblock that encloses a particular point (chosen from anywhere within the block) by exploring in both directions from the point, looking for the nearest boundary in each direction.

Finding all subblock boundaries in one step of evaluating F for all position concurrently.

Example: Forming a Table of Hashes

Once a block has been partitioned, the hash of each subblock can be calculated to form a table of hashes (FIG 24).

This table of hashes can be used to determine if a new subblock is identical to any of the subblocks whose hashes are in the table. To do this, the new subblock's hash is calculated and a check made to see if the hash is in the table.

In FIG. 24, the table of hashes looks like an array of hashes. However, the table of hashes could be stored in a wide variety of data structures (e.g. hash tables, binary trees).

Example Application: A File Comparison Utility

As the invention provides a new way of finding similarities between large volumes of data, it follows that it should find some application in the comparison of data.

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In one aspect, the invention could be used to determine the broad similarities between two files being compared by a file comparison utility. The utility would partition each of the two files into subblocks, organize the hashes of the subblocks somehow (e.g. using a hash table) to identify all identical subblocks, and then use this information as a framework for reporting similarities and differences between the two files.

In a similar aspect, the invention could be used to find similarities between the contents of large numbers of files in a file system. A utility incorporating the invention could read each file in an entire file system, partition each into subblocks and then insert the subblocks (or hashes of the subblocks) into one huge table (e.g. implemented by a hash table or a binary tree). If each entry in the table carried the name of the file containing it as well as the position of the subblock within the file, the table could later be used to identify those files containing identical portions of data.

If, in addition, a facility was added for recording and comparing the hashes of the entire contents of files and directory trees, a utility could be constructed that could identify all largely similar structures within a file system. Such a utility would be immensely useful when (say) attempting to merge the data on several similar backup tapes.

Example Application: A Fine-Grained Incremental Backup System

In a fine-grained incremental backup system, two entities E1 and E2 (e.g. two computers on a network) wish to repeatedly backup a file X at E1 such that the old version of the file Y at E2 will be updated to become a copy of the new version of the file X at E1 (without modifying X). The system could work as follows:

Each time E1 performs a backup operation, it partitions X into subblocks and writes the hashes of the subblocks to a shadow file S. It might also write a hash of the entire contents of X to the shadow file. After the backup has been completed, X will be the same as Y and so the shadow file S will correspond to both X and Y. Once X is again modified (during the normal operation of the computer system), S will correspond only to Y. S can then be used during the next backup operation.

To perform the backup, E1 compares the hash of Y (stored in S) against the hash of X to see if X has changed (it could also use the modification date file attribute of the file). If X hasn't changed, there is no need to perform any further backup action. If X has changed, E1 partitions X into subblocks, and compares the hashes of these subblocks with the hashes in the shadow file S, so as to find all identical hashes. Identical hashes identify identical subblocks in Y that can be transmitted by reference. E1 then transmits the file as a mixture of raw subblocks and references to subblocks whose hashes appear in S and which are therefore known to appear as subblocks in Y. E1 can also transmit references to subblocks already transmitted. References can take many forms including (without limitation):

A hash of the subblock.

The number of the subblock in the list of subblocks in Y.
The number of a subblock previously transmitted.

A range of any of the above.

Throughout this process, E1 can be constructing the new shadow file corresponding to X. FIG. 25 illustrates the backup process.

To reconstruct X from Y and D (the incremental backup information being sent from E1), E2 partitions Y into

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subblocks said calculates the hashes of the subblocks (It could do this in advance during the previous backup). It then processes the incremental backup information, copying subblocks that were transmitted raw and looking up the references either in Y or in the part of X already reconstructed.

Because information need only flow from E1 to E2 during the backup operation, there is no need for E1 and E2 to perform the backup operation concurrently. E1 can perform its side of the backup operation in isolation, producing an incremental backup file that can be later processed by E2.

There is a tradeoff between 1) the approximate ratio between the size of each file and that of its shadow, and 2) the mean subblock size. The higher the mean subblock size (as determined by the partitioning method used), the fewer subblocks per unit file length, and hence the shorter the shadow size per unit file length. However, increasing means subblock sizes implies increasing the granularity of backups which can cause an increase in the size of the incremental backup file. There is also a tradeoff between the shadow file size and the hash width. A shadow file that uses 128-bit hashes will be about twice as long as one that uses 64-bit hashes. All these tradeoffs must be considered closely when choosing an implementation.

Bytes	Description
16	MD5 digest of the file Y corresponding to this shadow file
16	MD5 digest of the first subblock in Y.
16	MD5 digest of the second subblock in Y.
...	...
16	MD5 digest of the last subblock in Y.
16	MD5 digest of the rest of this shadow file

The first field contains the MD5 digest (a form of cryptographic hash) of the entire contents of Y. This is included so that it can be copied to the incremental backup file so as to provide a check later that the incremental backup file is not being applied to the wrong version of Y. It could also be used to determine if any change has been made to X since the previous backup Y was taken. The first field is followed by a list of the MD5 digests of the subblocks in Y in the order in which they appear in Y. Finally, a digest of the contents of the shadow file (less this field) is included at the end so as to enable the detection of any corruption of the shadow file.

The format of the incremental backup file is as follows:

Bytes	Description
16	MD5 digest of Y.
16	MD5 digest of X.
...	Zero or more ITEMS
16	MD5 digest of the rest of the incremental backup file

The first two fields of the incremental backup file contain the MD5 digest of the old and new versions of the file. The hash of the new version X is calculated directly from X. The hash of the old version is obtained from the first field of the shadow file. These two values enable the remote backup entity E2 to check that:

The backup file Y (to be updated) is identical to the one from which the shadow file was generated.

The reconstructed X is identical to the original X.

The two checking fields are followed by a list of items followed by a checking digest of the rest of the incremental backup file.

Each item in the list of items describes one or more subblocks in the list of subblocks that can be considered to

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constitute X. There are three kinds of item, and each item commences with a byte having a value one, two, or three to indicate the kind of item. Here is a description of the content of each of the three kinds of item:

1. The 32-bit index of a subblock in Y. Because E2 possesses Y, it can partition Y itself to construct the same partitioning that was used to create the shadow file. Thus E1 doesn't need to send the hash of any subblock that is in both X and Y. Instead, it need only send the index of the subblock in the list of subblocks constituting Y. This list is represented by the list of hashes in the shadow file S. As 32-bits is wide enough for an index in practice, the saving gained by communicating a 32-bit index instead of a hash is 98 bits for each such item.
2. A pair of 32-bit numbers being the index of the first and last subblock of a range of subblocks in Y. Old and new versions of files often share large contiguous ranges of subblocks. The use of this kind of item allows such ranges to be represented using just 64 bits instead of a long run of instances of the first kind of item.
3. A 32-bit value containing the number of bytes in the subblock, followed by the raw content of the subblock. This kind of item is used if the subblock to be transmitted is not present in Y.

In the implementation, all the values are coded in little-endian form. Big-endian could be used equally as well.

The existing implementation could be further optimized by (without limitation):

Adding an additional kind of item that refers to subblocks in X already transmitted;

Adding an additional kind of item that refers to ranges of subblocks in X already transmitted;

Employing data compression techniques to compress the raw blocks in the third kind of item.

Using the first hash in the shadow file to check to see if the entire file has changed at all before performing the backup process described above.

Replacing hashes in S of subblocks in Y by references to other hashes in S (where the hashes (and hence subblocks) are identical). Repeated runs of hashes could also be replaced by pointers to ranges of hashes.

The scheme described above has been described in terms of a single file. However, the technique could be applied repeatedly to each of the files in a file system, thus providing a way to back up an entire file system. The shadow information for each file in the file system could be stored inside a separate shadow file for each file, or in a master shadow file containing the shadows for one or more (or all) files in the file system.

Although most redundancy in a file system is likely to be found within different versions of each file, there may be great similarities between versions of different files. For example, if a file is renamed, the "new" file will be identical to the "old" file. Such redundancy can be catered for by comparing the hashes of all the files in the old and new versions of a file system. In addition, similarities between different parts of different files can be exploited by comparing the hashes of subblocks of each file to be backed up with the hashes of the subblocks of the entire old version of the file system.

If E2 has lots of space, a further improvement could be for E1 to retain the shadows of all the previous versions of the file system, and for E2 to retain copies of all the previous versions of the file system. E1 could then refer to every block it has ever seen. This technique could also be applied on a file-by-file basis.

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In a further variant, the dependence on the ordering of subblocks could be abandoned, and E1 could simply keep a shadow file containing a list of the hashes of all the subblocks in the previous version (or versions) of the file or file system. E2 would then need to record only a single copy of each unique subblock it has ever received from E1.

Aspects of the backup application described in this section can be integrated cleanly into existing backup architecture by deploying the new mechanisms within the framework of existing ones. For example, the traditional methods for determining if a file has changed since the last backup (modification date, backup date and so on) can be used to see if a file needs to be backed up at all, before applying the new mechanisms.

Example Application: A Low-Redundancy File System

We now present an example of a low-redundancy file system that attempts to avoid storing different instances of the same data more than once. In this example, the file system is organized as shown in FIG. 26.

The bottom layer consists of a collection of unique subblocks of varying length that are stored somewhere on the disk. The middle layer consists of a hash table containing one entry for each subblock. Each entry consists of a cryptographic hash of the subblock, a reference count for the subblock, and a pointer to the subblock on disk. The hash table is indexed by some part of the cryptographic hash (e.g. the bottom 16 bits). Although a hash table is used in this example, many other data structures (e.g. a binary tree) could also be used to map cryptographic hashes to subblock entries. It would also be possible to index the subblocks directly without the use of cryptographic hashes.

The top layer consists of a table of files that binds filenames to lists of subblocks, each list being a list of indexes into the hash table. The reference count of the hash table records the number of references to the subblock that appear in the entire set of files in the file table. The issue of hash table "overflow" can be addressed using a variety of well-known overflow techniques such as that of attaching a linked list to each hash slot.

When a file is read, the list of hash table indexes is converted to pointers to subblocks of data using the hash table. If random access to the file is required, extra information about the length of the subblocks could be added to the file table and/or hash table so as to speed access.

Writing a file is more complicated. During a sequential write, the data being written is buffered until a subblock-boundary is reached (as determined by whatever boundary function is being used). The cryptographic hash of the new subblock is then calculated and used to look up the hash table. If the subblock is unique (i.e. there is no entry for the cryptographic hash), it is added to the data blocks on the disk and an entry is added to the hash table. A new subblock number is added to the list of blocks in the file table. If, on the other hand, the subblock already exists, the subblock need not be written to disk. Instead, the reference count of the already-existing subblock is incremented, and the subblock's hash table index is added to the list of blocks in the file's entry in the file table.

Random access writes are more involved, but essentially the same principles apply.

If a record were kept of subblocks created since the last backup, backing up this file system could be very efficient indeed.

One enhancement that could be made is to exploit unused disk space. Instead of automatically ignoring or overwriting

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subblocks whose reference count has dropped to zero, the low-redundancy file system could move them to a pool of unused subblocks. These subblocks, while not present in any file, could still form part of the subblock pool referred to when checking to see if incoming subblocks are already present in the file system. The space consumed by subblocks in the unused subblock pool would be recycled only when the disk was full. In the steady state, the "unused" portion of the disk would be filled by subblocks in the unused subblock pool.

Although this section has specifically described a low-redundancy file system, this aspect of the invention is really a general purpose storage system that could be applied at many levels and in many roles in information processing systems. For example:

The technique could be used to implement a low-redundancy virtual memory system. The contents of memory could be organized as a collection of subblocks.

The technique could be used to increase the efficiency of an on-chip cache.

Example Application: A Communication System

A method is now presented for reducing redundant transmissions in communications systems. Consider two entities E1 and E2, where E1 must transfer a block of data X to E2. E1 and E2 need never have communicated previously with each other.

The conventional way to perform the transmission is simply for E1 to transmit X to E2. However, here E1 first partitions X into subblocks and calculates the hash of each subblock using a hash function. It then transmits the hashes to E2. E2 then looks up the hashes in a table of hashes of all the subblocks it already possesses. E2 then transmits to E1 information (e.g. a list of subblock numbers) identifying the subblocks in X that E2 does not already possess. E1 then transmits just those subblocks.

Another way to perform the transaction would be for E2 to first transmit to E1 the hashes of all the subblocks it possesses (or perhaps a well chosen subset of them). E1 could then transmit references to subblocks in X already known to E2 and the actual contents of subblocks in X not known to E2. This scheme could be more efficient than the earlier scheme in cases where E2 possesses less subblocks than there are in X.

Another way to perform the transaction would be for E1 and E2 to conduct a more complicated conversation to establish which subblocks E2 possesses. For example, E2 could send E1 the hashes of just some of the subblocks it possesses (perhaps the most popular ones). E1 could then send to E2 the hashes of other subblocks in X. E2 could then reply indicating which of those subblocks it truly does not possess. E1 could then send to E2 the subblocks in X not possessed by E2.

In a more sophisticated system, E1 and E2 could keep track of the hashes of the subblocks possessed by the other. If either entity ever sent (for whatever reason) a reference to a subblock not possessed by the other entity, the latter entity could simply send back a request for the subblock to be transmitted explicitly and the former entity could send the requested subblock.

The communication application described above considers the case of just two communicants. However, there is no reason why the scheme could not be generalized to cover more than two communicants communicating with each

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other in private and in public (using broadcasts). For example, to broadcast a block, a computer C_1 could broadcast a list of the hashes of the block's subblocks. Computers $C_2 \dots C_N$ could then each reply indicating which subblocks they do not already possess. C_1 could then broadcast subblocks that many of the other computers do not possess, and send the subblocks missing from only a few computers to those computers privately.

All these techniques have the potential to greatly reduce the amount of information transmitted between computers.

These techniques would be very efficient if they were implemented on top of the file system described earlier, as the file system would already have performed the work of organizing all the data it possesses into indexed subblocks. The potential savings in communication that could be made if many different computer systems shared the same subblock partitioning algorithm suggests that some form of universal standardization on a particular partitioning method would be a worthy goal.

Example Application: A Subblock Server

Aspects of the invention could be used to establish a subblock server on a network so as to reduce network traffic. A subblock server could be located in a busy part of a network. It would consist of a computer that breaks each block of data it sees into subblocks, hashes the subblocks, and then stores them for future reference. Other computers on the network could send requests to the server for subblocks, the requests consisting of the hashes of subblocks the server might possess. The server would respond to each hash, returning either the subblock corresponding to the hash, or a message stating that the server does not possess a subblock corresponding to the hash.

Such a subblock server could be useful for localizing network traffic on the Internet. For example, if a subnetwork (even a large one for (say) an entire country) placed a subblock server on each of its major Internet connections, then (with the appropriate modification of various protocols) much of the traffic into the network could be eliminated. For example, if a user requested a file from a remote host on another network, the user's computer might issue the request and receive, in reply, not the file, but the hashes of the file's subblocks. The user's computer could then send the hashes to the local subblock server to see if the subblocks are present there. It would receive the subblocks that are present and then forward a request for the remaining subblocks to the remote host. The subblock server might notice the new subblocks flowing through it and archive them for future reference. The entire effect could be to eliminate most repeated data transfers between the subnetwork and the rest of the Internet. However, the security implications of schemes such as these would need to be closely investigated before there were deployed.

A further step could be to create "virtual" subblock servers that store the hashes of subblocks and their location on the Internet rather than the subblocks and their hashes.

I claim:

1 A method for organizing a block b of digital data for storage, communication, or comparison, comprising the step of:

partitioning said block b into a plurality of subblocks at least one position $k[k+1]$ within said block, for which $b[k-A+1 \dots k+B]$ satisfies a predetermined constraint, and

wherein A and B are natural numbers.

2 The method of claim 1, wherein the constraint comprises the hash of at least a portion of $b[k-A+1 \dots k+B]$.

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3 The method of claim 1, further comprising the step of:
locating the nearest subblock boundary on a side of a
position $plp+1$ within said block, said locating step
comprising the step of:

evaluating whether said predetermined constraint is sat- 5
isfied at each position $k|k+1$ for increasing or decreas-
ing k ,

wherein k starts with the value p .

4 The method of claim 1, wherein at least one bound is 10
imposed on the size of at least one of said plurality of
subblocks

5 The method of claim 1, wherein additional subblocks
are formed from at least one group of subblocks

6 The method of claim 1, wherein an additional hierarchy 15
of subblocks is formed from at least one group of contiguous
subblocks.

7 The method of claim 1, further comprising the step of:
calculating the hash of each of at least one of said plurality
of subblocks

8 The method of claim 1, further comprising the step of: 20
forming a projection of said block, being an ordered or
unordered collection of elements, wherein each element
consists of a subblock, an identity of a subblock,
or a reference of a subblock.

9 The method of claim 1, wherein said subblocks are
compared by comparing the hashes of said subblocks

10 The method of claim 1, wherein subsets of identical
subblocks within a group of one or more subblocks are
found by inserting each subblock, an identity of each
subblock, a reference of each subblock, or a hash of each
subblock into a data structure

11 A method for comparing one or more blocks, com-
prising the steps of:

organizing a block b of digital data for the purpose of 35
comparison, comprising the step of:

partitioning said block b into a plurality of subblocks at
at least one position $k|k+1$ within said block;

for which $b[k-A+1 \dots k+B]$ satisfies a predetermined 40
constraint; and
wherein A and B are natural numbers,

forming a projection of each said block, being a collection
of elements, wherein each element comprises a selected
one of a subblock, an identity of a subblock, and a
reference of a subblock, and 45

comparing the elements of said projections of said blocks

12 A method for representing one or more blocks com-
prising a collection of subblocks and block representatives
which are mapped to lists of entries which identify sub-
blocks; said method comprising the step of modifying one of
said blocks including the steps of: 50

partitioning said block into a plurality of subblocks at
at least one position $k|k+1$ within said block, for which
 $b[k-A+1 \dots k+B]$ satisfies a predetermined constraint,
and wherein A and B are natural numbers, 55

adding to said collection of subblocks zero or more
subblocks which are not already in said collection, and
updating said subblock list associated with said modified
block 60

13 A method for representing one or more blocks com-
prising a collection of subblocks and block representatives
which are mapped to lists of entries which identify sub-
blocks; said method comprising the step of modifying one of
said blocks including the steps of: 65

partitioning said block into a plurality of subblocks at
at least one position $k|k+1$ within said block, for which

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$b[k-A+1 \dots k+B]$ satisfies a predetermined constraint,
and wherein A and B are natural numbers,

removing from said collection of subblocks zero or more
subblocks, and

updating said subblock list associated with said modified
block

14 A method for representing one or more blocks com-
prising a collection of subblocks and block representatives
which are mapped to lists of entries which identify sub-
blocks; said method comprising the step of modifying one of
said blocks including the steps of:

partitioning said block into a plurality of subblocks at
at least one position $k|k+1$ within said block, for which
 $b[k-A+1 \dots k+B]$ satisfies a predetermined constraint,
and wherein A and B are natural numbers, 15

adding to said collection of subblocks zero or more
subblocks that are not already in the collection,

removing from said collection of subblocks zero or more
subblocks, and

updating said subblock list associated with said modified
block. 20

15 A method for an entity $E1$ to communicate a block X
to $E2$ where $E1$ possesses the knowledge that $E2$ possesses
a group of Y subblocks $Y_1 \dots Y_m$, comprising the steps of:

partitioning said block X into a plurality of subblocks
 $X_1 \dots X_n$ at at least one position $k|k+1$ within said
block, for which $X[k-A+1 \dots k+B]$ satisfies a prede-
termined constraint, and wherein A and B are natural
numbers, and 25

transmitting from $E1$ to $E2$ the contents of zero or more
subblocks in X_1 and the remaining subblocks as refer-
ences to subblocks in $Y_1 \dots Y_m$, and to subblocks
transmitted. 30

16 A method for an entity $E1$ to communicate one or
more subblocks of a group X of subblocks $X_1 \dots X_n$ to $E2$
where $E1$ possesses the knowledge that $E2$ possesses a block
 Y , comprising the steps of:

partitioning said block Y into a plurality of subblocks
 $Y_1 \dots Y_m$ at at least one position $k|k+1$ within said
block, for which $Y[k-A+1 \dots k+B]$ satisfies a prede-
termined constraint, and wherein A and B are natural
numbers, and 40

transmitting from $E1$ to $E2$ the contents of zero or more
subblocks in X , and the remaining subblocks as refer-
ences to subblocks in Y , and to subblocks already
transmitted. 45

17 A method for an entity $E1$ to communicate a block X
to $E2$ where $E1$ possesses the knowledge that $E2$ possesses
a block Y , comprising the steps of: 50

partitioning said block X into a plurality of subblocks
 $X_1 \dots X_n$ at at least one position $k|k+1$ within said
block, for which $X[k-A+1 \dots k+B]$ satisfies a prede-
termined constraint, and wherein A and B are natural
numbers, 55

partitioning said block Y into a plurality of subblocks
 $Y_1 \dots Y_m$ at at least one position $k|k+1$ within said
block, for which $Y[k-A+1 \dots k+B]$ satisfies a prede-
termined constraint, and wherein A and B are natural
numbers, and 60

transmitting from $E1$ to $E2$ the contents of zero or more
subblocks in X , and the remaining subblocks as refer-
ences to subblocks in Y , and to subblocks already
transmitted

18 A method for constructing a block D from a block X
and a group Y of subblocks $Y_1 \dots Y_m$ such that X can be
constructed from Y and D , comprising the steps of:

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partitioning said block X into a plurality of subblocks $X_1 \dots X_n$ at at least one position $k|k+1$ within said block, for which $X[k-A+1 \dots k+B]$ satisfies a predetermined constraint, and wherein A and B are natural numbers, and

constructing D from a selected at least one of:
the contents of zero or more subblocks in X,
references to zero or more subblocks in Y, and
references to zero or more subblocks in D.

19. A method for constructing a block D from a group X of subblocks $X_1 \dots X_n$ and a block Y such that X can be constructed from Y and D, comprising the steps of:

partitioning said block Y into a plurality of subblocks $Y_1 \dots Y_m$ at at least one position $k|k+1$ within said block, for which $Y[k-A+1 \dots k+B]$ satisfies a predetermined constraint, and wherein A and B are natural numbers, and

constructing D from a selected at least one of:
the contents of zero or more subblocks in X,
references to zero or more subblocks in Y, and
references to zero or more subblocks in D.

20. A method for constructing a block D from a block X and a block Y such that X can be constructed from Y and D, comprising the steps of:

partitioning said block X into a plurality of subblocks $X_1 \dots X_n$ at at least one position $k|k+1$ within said block, for which $X[k-A+1 \dots k+B]$ satisfies a predetermined constraint, and wherein A and B are natural numbers,

partitioning said block Y into a plurality of subblocks $Y_1 \dots Y_m$ at at least one position $k|k+1$ within said block, for which $Y[k-A+1 \dots k+B]$ satisfies a predetermined constraint, and wherein A and B are natural numbers, and

constructing D from a selected at least one of:
the contents of zero or more in X,
references to zero or more subblocks in Y, and
references to zero or more subblocks in D.

21. A method for constructing a block D from a block X and a projection Y said projection comprising a collection of elements wherein said elements comprises a subblock in Y, an identity of a subblock in Y, or a reference of a subblock in Y, such that X can be constructed from Y and D, comprising the steps of:

partitioning said block X into a plurality of subblocks $X_1 \dots X_n$ at at least one position $k|k+1$ within said block, for which $X[k-A+1 \dots k+B]$ satisfies a predetermined constraint, and wherein A and B are natural numbers, and

constructing D from a selected at least one of:
the contents of zero or more in X,
references to zero or more subblocks in Y, and
references to zero or more subblocks in D.

22. A method for constructing a block X from a block Y and a block D, comprising the steps of:

partitioning said block Y into a plurality of subblocks $Y_1 \dots Y_m$ at at least one position $k|k+1$ within said block, for which $Y[k-A+1 \dots k+B]$ satisfies a predetermined constraint, and wherein A and B are natural numbers, and

constructing X from D and Y by constructing the subblocks of X based on a selected at least one of:
subblocks contained within D,
references in D to subblocks in Y, and
references to D to subblocks in D.

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23. A method for constructing a group X of subblocks $X_1 \dots X_n$ from a block Y and a block D, comprising the steps of:

partitioning said block Y into a plurality of subblocks $Y_1 \dots Y_m$ at at least one position $k|k+1$ within said block, for which $Y[k-A+1 \dots k+B]$ satisfies a predetermined constraint, and wherein A and B are natural numbers, and

constructing $X_1 \dots X_n$ from D and Y based on a selected at least one of:
subblocks contained within D,
references in D to subblocks in Y, and
references to D to subblocks in D.

24. A method for communicating a data block X from one entity E1 to another entity E2, comprising the steps of:

partitioning said block X into a plurality of subblocks $X_1 \dots X_n$ at at least one position $k|k+1$ within said block, for which $X[k-A+1 \dots k+B]$ satisfies a predetermined constraint, and wherein A and B are natural numbers,

transmitting from E1 to E2 an identity of at least one subblock,

transmitting from E2 to E1 information communicating the presence or absence of subblocks at E2, and

transmitting from E1 to E2 at least the subblocks identified as not being present at E2.

25. A method for communicating a block X from one entity E1 to another entity E2, comprising the steps of:

partitioning said block X into a plurality of subblocks $X_1 \dots X_n$ at at least one position $k|k+1$ within said block, for which $X[k-A+1 \dots k+B]$ satisfies a predetermined constraint, and wherein A and B are natural numbers,

transmitting from E2 to E1 information communicating the presence or absence at E2 of members of a group Y of subblocks $Y_1 \dots Y_m$, and

transmitting from E1 to E2 the contents of zero or more subblocks in X, and the remaining subblocks as references to subblocks in $Y_1 \dots Y_m$ and to subblocks already transmitted.

26. A method for an entity E2 to communicate to an entity E1 the fact that E2 possesses a block Y, comprising the steps of:

partitioning said block Y into a plurality of subblocks $Y_1 \dots Y_m$ at at least one position $k|k+1$ within said block, for which $Y[k-A+1 \dots k+B]$ satisfies a predetermined constraint, and wherein A and B are natural numbers, and

transmitting from E2 to E1 references of the subblocks $Y_1 \dots Y_m$.

27. A method for an entity E1 to communicate a subblock X_1 to an entity E2, comprising the steps of:

partitioning said block X into a plurality of subblocks $X_1 \dots X_n$ at at least one position $k|k+1$ within said block, for which $X[k-A+1 \dots k+B]$ satisfies a predetermined constraint, and wherein A and B are natural numbers,

transmitting from E2 to E1 an identity of X_1 ,

transmitting X_1 from E1 to E2.

28. An apparatus for organizing a block b of digital data for storage, communication, or comparison, comprising means for partitioning said block b into a plurality of subblocks at at least one position $k|k+1$ within said block, for which $b[k-A+1 \dots k+B]$ satisfies a predetermined constraint, and wherein A and B are natural numbers.

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29. The apparatus of claim 28, in which the constraint comprises the hash of some or all of $b[k-A+1 \dots k+B]$

30. The apparatus of claim 28, further comprising

means for locating the nearest subblock boundary on a side of a position $p|p+1$ within said block, said means 5
for locating comprising:

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means for evaluating whether said predetermined constraint is satisfied at each position $k|k+1$ for increasing or decreasing k ,
wherein k starts with the value p .

* * * * *

CIVIL COVER SHEET

JS 44

(Rev. 12/96)

The JS-44 civil cover sheet and the information contained herein neither replace nor supplement the filing and service of pleadings or other papers as required by law, except as provided by local rules of court. This form, approved by the Judicial Conference of the United States in September 1974, is required for the use of the Clerk of Court for the purpose of initiating the civil docket sheet. (SEE INSTRUCTIONS ON THE REVERSE OF THE FORM.)

I.(a) PLAINTIFF
RIVERBED TECHNOLOGY, INC.

DEFENDANTS

QUANTUM CORPORATION, a Delaware corporation;
A.C.N. 120 786 012 PTY. LTD., an Australian company and
ROCKSOFT LTD., an Australian company

(b) COUNTY OF RESIDENCE OF FIRST LISTED PLAINTIFF _____
(EXCEPT IN U S PLAINTIFF CASES)

COUNTY OF RESIDENCE OF FIRST LISTED DEFENDANT _____
(IN U S PLAINTIFF CASES ONLY)
NOTE: IN LAND CONDEMNATION CASES, USE THE LOCATION OF THE TRACT
OF LAND INVOLVED

(c) ATTORNEYS (FIRM NAME, ADDRESS, AND TELEPHONE NUMBER)
Jeffrey L. Moyer
Richards, Layton & Finger
One Rodney Square - P O Box 551
Wilmington, DE 19899
(302) 651-7700

ATTORNEYS (IF KNOWN)

II. BASIS OF JURISDICTION (PLACE AN X IN ONE BOX ONLY)

- ☐ 1 U.S. Government Plaintiff ☒ 3 Federal Question Plaintiff (U S Government Not a Party)
- ☐ 2 U S Government Defendant ☐ 4 Diversity (Indicate Citizenship of Parties in Item III)

III. CITIZENSHIP OF PRINCIPAL PARTIES (PLACE AN "X" IN ONE BOX

(For Diversity Cases Only) FOR PLAINTIFF AND ONE BOX FOR DEFENDANT

- | | | | | | |
|---|----------------------------|----------------------------|---|----------------------------|----------------------------|
| | PTF | DEF | | PTF | DEF |
| Citizen of This State | <input type="checkbox"/> 1 | <input type="checkbox"/> 1 | Incorporated or Principal Place of Business in This State | <input type="checkbox"/> 4 | <input type="checkbox"/> 4 |
| Citizen of Another State | <input type="checkbox"/> 2 | <input type="checkbox"/> 2 | Incorporated and Principal Place of Business in Another State | <input type="checkbox"/> 5 | <input type="checkbox"/> 5 |
| Citizen or Subject of a Foreign Country | <input type="checkbox"/> 3 | <input type="checkbox"/> 3 | Foreign Nation | <input type="checkbox"/> 6 | <input type="checkbox"/> 6 |

IV. NATURE OF SUIT (PLACE AN X IN ONE BOX ONLY)

CONTRACT	TORTS	FORFEITURE/PENALTY	BANKRUPTCY	OTHER STATUTES
<input type="checkbox"/> 110 Insurance <input type="checkbox"/> 120 Marine <input type="checkbox"/> 130 Miller Act <input type="checkbox"/> 140 Negotiable Instrument <input type="checkbox"/> 150 Recovery of Overpayment & Enforcement of Judgment <input type="checkbox"/> 151 Medicare Act <input type="checkbox"/> 152 Recovery of Defaulted Student Loans (excl Veterans) <input type="checkbox"/> 153 Recovery of Overpayment of Veteran's Benefits <input type="checkbox"/> 160 Stockholder's Suits <input type="checkbox"/> 190 Other Contract <input type="checkbox"/> 195 Contract Product Liability	PERSONAL INJURY <input type="checkbox"/> 310 Airplane <input type="checkbox"/> 315 Airplane Product Liability <input type="checkbox"/> 320 Assault, Libel & Slander <input type="checkbox"/> 330 Federal Employers' Liability <input type="checkbox"/> 340 Marine <input type="checkbox"/> 345 Marine Product Liability <input type="checkbox"/> 350 Motor Vehicle <input type="checkbox"/> 355 Motor Vehicle Product Liability <input type="checkbox"/> 360 Other Personal Injury PERSONAL INJURY <input type="checkbox"/> 362 Personal Injury - Med Malpractice <input type="checkbox"/> 365 Personal Injury - Product Liability <input type="checkbox"/> 368 Asbestos Personal Injury Product Liability PERSONAL PROPERTY <input type="checkbox"/> 370 Other Fraud <input type="checkbox"/> 371 Truth in Lending <input type="checkbox"/> 380 Other Personal Property Damage <input type="checkbox"/> 385 Property Damage Product Liability	<input type="checkbox"/> 610 Agriculture <input type="checkbox"/> 620 Other Food & Drug <input type="checkbox"/> 625 Drug Related Seizure of Property 21 USC 881 <input type="checkbox"/> 630 Liquor Laws <input type="checkbox"/> 640 R.R. & Truck <input type="checkbox"/> 650 Airline Regs. <input type="checkbox"/> 660 Occupational Safety/Health <input type="checkbox"/> 690 Other LABOR <input type="checkbox"/> 710 Fair Labor Standards Act <input type="checkbox"/> 720 Labor/Mgmt. Relations <input type="checkbox"/> 730 Labor/Mgmt. Reporting & Disclosure Act <input type="checkbox"/> 740 Railway Labor Act <input type="checkbox"/> 790 Other Labor Litigation <input type="checkbox"/> 791 Empl Ret. Inc. Security Act	<input type="checkbox"/> 422 Appeal 28 USC 158 <input type="checkbox"/> 423 Withdrawal 28 USC 157 PROPERTY RIGHTS <input type="checkbox"/> 820 Copyrights <input checked="" type="checkbox"/> 830 Patent <input type="checkbox"/> 840 Trademark SOCIAL SECURITY <input type="checkbox"/> 861 HIA (1395ff) <input type="checkbox"/> 862 Black Lung (923) <input type="checkbox"/> 863 DIWC/DIWW (405(g)) <input type="checkbox"/> 864 SSID Title XVI <input type="checkbox"/> 865 RSI (405(g)) FEDERAL TAX SUITS <input type="checkbox"/> 870 Taxes (U S Plaintiff or Defendant) <input type="checkbox"/> 871 IRS - Third Party 26 USC 7609	<input type="checkbox"/> 400 State Reappointment <input type="checkbox"/> 410 Antitrust <input type="checkbox"/> 430 Banks and Banking <input type="checkbox"/> 450 Commerce/ICC Rates/etc. <input type="checkbox"/> 460 Deportation <input type="checkbox"/> 470 Racketeer Influenced and Corrupt Organizations <input type="checkbox"/> 810 Selective Service <input type="checkbox"/> 850 Securities/Commodities/Exchange <input type="checkbox"/> 875 Customer Challenge 12 USC 3410 <input type="checkbox"/> 891 Agricultural Acts <input type="checkbox"/> 892 Economic Stabilization Act <input type="checkbox"/> 893 Environmental Matters <input type="checkbox"/> 894 Energy Allocation Act <input type="checkbox"/> 895 Freedom of Information Act <input type="checkbox"/> 900 Appeal of Fee Determination Under Equal Access to Justice <input type="checkbox"/> 950 Constitutionality of State Statutes <input type="checkbox"/> 890 Other Statutory Actions
REAL PROPERTY <input type="checkbox"/> 210 Land Condemnation <input type="checkbox"/> 220 Foreclosure <input type="checkbox"/> 230 Rent Lease & Eject <input type="checkbox"/> 240 Torts to Land <input type="checkbox"/> 245 Tort Product Liability <input type="checkbox"/> 290 All Other Real Property	CIVIL RIGHTS <input type="checkbox"/> 441 Voting <input type="checkbox"/> 442 Employment <input type="checkbox"/> 443 Housing/Accommodations <input type="checkbox"/> 444 Welfare <input type="checkbox"/> 440 Other Civil Rights PRISONER PETITIONS <input type="checkbox"/> 510 Motions to Vacate Sentence <input type="checkbox"/> Habeas Corpus: <input type="checkbox"/> 530 General <input type="checkbox"/> 535 Death Penalty <input type="checkbox"/> 540 Mandamus & Other <input type="checkbox"/> 550 Civil Rights <input type="checkbox"/> 555 Prison Condition			

V. ORIGIN (PLACE AN X IN ONE BOX ONLY)

- ☒ 1 Original Proceeding ☐ 2 Removed from State Court ☐ 3 Remanded from Appellate Court ☐ 4 Reinstated or Reopened ☐ 50 Transferred from another district (specify) _____ ☐ 6 Multidistrict Litigation ☐ 7 Appeal to District Judge from Magistrate Judgment

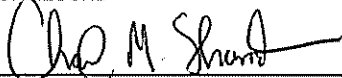
VI. CAUSE OF ACTION (CITE THE U S CIVIL STATUTE UNDER WHICH YOU ARE FILING AND WRITE A BRIEF STATEMENT OF CAUSE DO NOT CITE JURISDICTIONAL STATUTES UNLESS DIVERSITY) **Declaratory Judgment/Patent Infringement 28 USC §§ 1331, 1338**

VII. REQUESTED IN COMPLAINT: CHECK IF THIS IS A CLASS ACTION ☐ DEMAND \$ _____ CHECK YES only if demanded in complaint: JURY DEMAND ☒ YES ☐ NO

VIII. RELATED CASE(S) (See instructions): IF ANY Judge _____ Docket Number _____

DATE SIGNATURE OF ATTORNEY OF RECORD

January 9, 2008



FOR OFFICE USE ONLY

RECEIPT # _____ AMOUNT _____ APPLYING IFP _____ JUDGE _____ MAG JUDGE _____

INSTRUCTIONS FOR ATTORNEYS COMPLETING CIVIL COVER SHEET FORM JS-44

Authority For Civil Cover Sheet

The JS-44 civil cover sheet and the information contained herein neither replaces nor supplements the filings and service of pleading or other papers as required by law, except as provided by local rules of court. This form, approved by the Judicial Conference of the United States in September 1974, is required for the use of the Clerk of Court for the purpose of initiating the civil docket sheet. Consequently a civil cover sheet is submitted to the Clerk of Court for each civil complaint filed. The attorney filing a case should complete the form as follows:

I. (a) Plaintiffs - Defendants. Enter names (last, first, middle initial) of plaintiff and defendant. If the plaintiff or defendant is a government agency, use only the full name or standard abbreviations. If the plaintiff or defendant is an official within a government agency, identify first the agency and then the official, giving both name and title.

(b) County of Residence. For each civil case filed, except U.S. plaintiff cases, enter the name of the county where the first listed plaintiff resides at the time of filing. In U.S. plaintiff cases, enter the name of the county in which the first listed defendant resides at the time of filing. (NOTE: In land condemnation cases, the county of residence of the "defendant" is the location of the tract of land involved.)

(c) Attorneys. Enter firm name, address, telephone number, and attorney of record. If there are several attorneys, list them on an attachment, noting in this section "(see attachment)".

II. Jurisdiction. The basis of jurisdiction is set forth under Rule 8 (a), F.R.C.P., which requires that jurisdictions be shown in pleadings. Place an "X" in one of the boxes. If there is more than one basis of jurisdiction, precedence is given in the order shown below.

United States plaintiff (1) Jurisdiction is based on 28 U.S.C. 1345 and 1348. Suits by agencies and officers of the United States are included here.

United States defendant (2) When the plaintiff is suing the United States, its officers or agencies, place an X in this box.

Federal question (3) This refers to suits under 28 U.S.C. 1331, where jurisdiction arises under the Constitution of the United States, an amendment to the Constitution, an act of Congress or a treaty of the United States. In cases where the U.S. is a party, the U.S. plaintiff or defendant code takes precedence, and box 1 or 2 should be marked.

Diversity of citizenship (4) This refers to suits under 28 U.S.C. 1332, where parties are citizens of different states. When Box 4 is checked, the citizenship of the different parties must be checked. (See Section III below; federal question actions take precedence over diversity cases.)

III. Residence (citizenship) of Principal Parties. This section of the JS-44 is to be completed if diversity of citizenship was indicated above. Mark this section for each principal party.

IV. Cause of Action. Report the civil statute directly related to the cause of action and give a brief description of the cause.

V. Nature of Suit. Place an "X" in the appropriate box. If the nature of suit cannot be determined, be sure the cause of action, in Section IV above, is sufficient to enable the deputy clerk or the statistical clerks in the Administrative Office to determine the nature of suit. If the cause fits more than one nature of suit, select the most definitive.

VI. Origin. Place an "X" in one of the seven boxes.

Original Proceedings (1) Cases which originate in the United States district courts.

Removed from State Court (2) Proceedings initiated in state courts may be removed to the district courts under Title 28 U.S.C., Section 1441. When the petition for removal is granted, check this box.

Remanded from Appellate Court (3) Check this box for cases remanded to the district court for further action. Use the date of remand as the filing date.

Reinstated or Reopened (4) Check this box for cases reinstated or reopened in the district court. Use the reopening date as the filing date.

Transferred from Another District (5) For cases transferred under Title 28 U.S.C. Section 1404(a). Do not use this for within district transfers or multidistrict litigation transfers.

Multidistrict Litigation (6) Check this box when a multidistrict case is transferred into the district under authority of Title 28 U.S.C. Section 1407. When this box is checked, do not check (5) above.

Appeal to District Judge from Magistrate Judgment (7) Check this box for an appeal from a magistrate's decision.

VII. Requested in Complaint. Class Action. Place an "X" in this box if you are filing a class action under Rule 23, F.R.C.P.

Demand. In this space enter the dollar amount (in thousands of dollars) being demanded or indicate other demand such as a preliminary injunction.

Jury Demand. Check the appropriate box to indicate whether or not a jury is being demanded.

VIII. Related Cases. This section of the JS-44 is used to reference relating pending cases if any. If there are related pending cases, insert the docket numbers and the corresponding judge names for such cases.

Date and Attorney Signature. Date and sign the civil cover sheet.
(rev. 07/89)

AO FORM 85 RECEIPT (REV. 9/04)

United States District Court for the District of Delaware

Civil Action No. 08-016

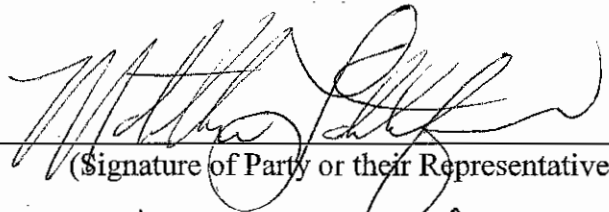
ACKNOWLEDGMENT
OF RECEIPT FOR AO FORM 85

NOTICE OF AVAILABILITY OF A
UNITED STATES MAGISTRATE JUDGE
TO EXERCISE JURISDICTION

I HEREBY ACKNOWLEDGE RECEIPT OF 4 COPIES OF AO FORM 85.

1/9/08

(Date forms issued)


(Signature of Party or their Representative)

Matthew Latchford

(Printed name of Party or their Representative)

Note: Completed receipt will be filed in the Civil Action